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# The urban heat island effect in a small Mediterranean city of high summer temperatures and cooling energy demands

E. Vardoulakis *, D. Karamanis, A. Fotiadi, G. Mihalakakou

*Department of Environmental & Natural Resources Management, University of Ioannina, Seferi 2, Agrinio, Greece*

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**Abstract**

The results of an urban heat island (UHI) study during summer and winter through a full year period (2010–2011) in a small city of western Greece are presented and analyzed. The specific research target was to identify the existence of the phenomenon, measure its intensity and investigate the parameters that may be associated with the appearance of the UHI. A network of air temperature sensors was installed in nine different locations of the city and measurements were recorded every 10 min. Extensive statistical analysis revealed strong UHI intensities reaching values up to 6.0 °C with a mean intensity of 3.8 °C during nocturnal hours of August. Heat island in the city proved to be a night dominating phenomenon while wind velocity was found to wield great impact on the ventilation and cooling effect of the city. During summer, early in the morning many locations in the city centre remained cooler than the rural environment while a heat island was observed on a monthly basis during winter. In order to determine the variation of the current energy needs due to the UHI effect, the heating degree hours during winter were calculated and were found to be much lower in the city centre than in the rural area (12.6–14.2% reduction). During summer, a high increase in the cooling degree hours of the city was observed in comparison to the rural environment, with a maximum difference of 36.3% for August 2010.


*Keywords:* Urban heat island; Microclimate; Heating; Cooling energy needs

## 1. Introduction

The world has experienced unprecedented urban growth in recent decades. In 2008, there were more than 400 cities over 1 million and 19 over 10 million. More developed nations were about 74% urban, while 44% of residents of less developed countries lived in urban areas. However, urbanization is occurring rapidly in many less developed countries. It is expected that 70% of the world population will be urban by 2050, and that most urban growth will occur in less developed countries (Population Reference Bureau, 2010).

Changes of land surface in cities affect the storage and radiative transfer of heat and its partitioning into sensible and latent components. Thus air temperature values in areas of high building density are usually higher than those of the surrounding rural country. This phenomenon, referred as UHI, was first documented by Howard in 1883, and is the most validated phenomenon of climatic change, consisted the strongest feature of urbanization (Landsberg, 1981). The highest air temperature difference between urban and rural areas defines the urban heat island intensity (UHII). Elevation of air temperature increases the building cooling energy demand, which results in higher pollution emissions. The opposite effect of lower air temperature of the urban central area

* Corresponding author. Tel.: +30 26410 74210; fax: +30 26410 39576.
*E-mail addresses:* evardoul@cc.uoi.gr (E. Vardoulakis), dkaraman@cc.uoi.gr (D. Karamanis), afotiadi@cc.uoi.gr (A. Fotiadi), pmichala@cc.uoi.gr (G. Mihalakakou).

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**Nomenclature**

| | | | |
|---|---|---|---|
| $\Delta T_{U-R}$ | urban–rural temperature difference | $t_{bal}$ | base temperature |
| CDCs | cooling degree hours | $T_u$ | urban station temperature |
| HDCs | heating degree hours | $T_r$ | rural station temperature |
| $H/W$ | height to width ratio | UHI | urban heat island |
| RCMs | Regional Climate Models | UHII | urban heat island intensity |
| S.D. | standard deviation | UCI | urban cool island |
| SPSSs | Statistical Product and Service Solutions | | |

compared to rural areas or the so called Urban Cool Island (UCI), especially during the morning has been also reported (Shigeta et al., 2009; Watkins et al., 2002a; Chang et al., 2007). In general, among the main mechanisms contributing to the UHI phenomenon are building and road geometry, thermal and optical properties of materials used in urban spar, anthropogenic heat and lack of evaporation in the cities (Kolokotroni and Giridharan, 2008; Santamouris et al., 2001; Rizwan et al., 2008). It also may be affected by air pollution and aerosols. Thus, it is critical to understand and improve our knowledge for the phenomenon in small cities, to upgrade energy efficiency in the urban building stock and achieve higher quality of life standards.

UHI has many harmful effects like high city temperatures, environment degradation and increase of energy demand. In many cases higher death rates had been reported during summer heat waves (Buechley et al., 1972; Smoyer, 1998; Johnson and Wilson, 2008; Gabriel Katharina and Endlicher, 2011; Hattis et al., 2012). Hence, many researchers around the world have intensively studied the UHI effect in the last 30 years. In Barcelona, a methodology of recording temperature transects along the road by car was used (Carmen Moreno-Garcia, 1993). By examining annual means of temperature differences, it was found that the city centre was slightly cooler than the periphery during day. In contrast, the city centre was 2.9 °C warmer than the airport during night. Additionally, average values along the transects verify that the highest UHI intensity exceeded 8.0 °C, but rarely extended above 9.0 °C.

Unger (1996) showed that the heat island effect reaches 2.9 °C during anticyclonic conditions in a medium-sized town in Hungary. This intensity is mainly achieved during days of clear sky, calm or slight wind and absence of precipitation, conditions that favour the development of heat island. In general, this analysis shows that the UHI intensity in medium sized towns depends on the general meteorological conditions to a large extent.

In Paris, Dupont et al. (1999) compared measurements between two different sites (urban and rural) that were collected during an experiment that has been performed during winter of 1995. It was found that the heat island intensity lies between 0 °C and 6.0 °C with a maximum value at 8:00 in the morning.

In a small city in coastal Portugal, Pinto and Orgaz Manso (2000) measured temperature differences between urban and rural areas by using the method of driving car for 48 nights during summer, autumn and winter, between 23.00 and 01.00 h. Results show that Aveiro, although a small city, has an urban morphology and climate that occasionally reaches a heat island intensity of 7.5 °C.

In Bassel, Switzerland an experimental network of seven stations was established and data were recorded during 2001–2002. Results show a heat island intensity of 3.0 °C, which was observed after sunset, while during night, intensity values were lower (Christen and Vogt, 2004).

In Sweden, a study was carried out by Svensson (2004) in Göteborg, by using 16 permanent stations and examining fish-eye photographs to analyze height/width ratios and sky view factor. Also, air temperature measurements were performed by using specially equipped cars. Results show a strong relationship between sky view factor and air temperature during clear, calm nights.

In Rome, an urban canopy layer model was developed to simulate and describe urban climate and heat storage in an urban setting, by taking into account many atmospheric parameters (Bonacquisti et al., 2005). Both simulated results and experimental observation agree that the phenomenon is nocturnal and is present both during winter (2.0 °C) and summer (5.0 °C).

Kolokotroni and Giridharan (2008) have recently indicated that the intensity of the phenomenon in London area reaches 8.9 °C on occasion, while there are time periods, where a cool island is observed. The selection of the variables to analyze the UHI in every city and its attribute to the changes in outdoor temperatures is crucial. As demonstrated by Okada et al. (2008), the mean temperature in Tokyo has increased 3.0–4.0 °C in the last 100 years. Also, the number of nights where temperature does not fall below 25.0 °C has risen from 10–15 nights before a decade, to 40 nights at 2008.

In Greece, a number of research projects-most of which were carried out in Athens-using temperature dataloggers and meteorological stations have been published during the last decade and proved the existence of the

Table 1
Characteristics of cities and mean UHI intensity determination.

| Town-area ($km^2$) | Population and number of temperature sensors used | Temperature station spatial resolution ($km^2$/sensor) | Mean heat island intensity (°C) | Summer maximum mean monthly temperature (°C) [5] | | |
|---|---|---|---|---|---|---|
| | | | | June | July | August |
| Athens 412 $km^2$ | 3,074,160 residents 25 sensors | 16.48 [1] | Close to 5.0 °C during summer | 28.7 | 31.8 | 31.7 |
| Thessaloniki 111.7 $km^2$ | 790,824 residents 7 sensors | 15.96 [2] | 2.0 to 4.0 °C during the summer | 29.2 | 31.5 | 31.1 |
| Volos 27.67 $km^2$ | 144,449 residents 4 sensors (2 of them in the UHII estimation) | 13.84 [3] | 2.0 °C during both seasons (summer and winter) | 29.0 | 31.0 | 30.7 |
| Chania 12.56 $km^2$ | 65,838 residents 12 sensors (9 of them used in the UHII estimation) | 1.40 [4] | 2.6 °C during the summer | 28.7 | 30.3 | 30.0 |
| Agrinio 12.46 $km^2$ | 94,181 residents 8 sensors | 1.55 [current study] | 3.8 °C during nights of August 2010 | 30.4 | 33.2 | 33.6 |

[1] Giannopoulou et al. (2010a,b); [2] Giannaros and Melas (2012); [3] Papanastasiou and Kittas (2011); [4] Kolokotsa et al. (2009) and [5] Retrieved from www.hnms.gr; Hellenic National Meteorological Service (2012) (Data period 1956–1997).

phenomenon (Table 1). As demonstrated by Santamouris et al. (2001), the effect results in doubling occasionally the cooling load in urban buildings, while the peak electricity load for cooling purposes may be tripled for high air temperatures.

Although the heat island is the most documented phenomenon of climate change in the urban environment, studies have been mainly concentrated on high populated cities. Consequently, there is still lack of research concerning the intensity of the phenomenon in small-sized cities (Santamouris 2007; Blazejczyk et al., 2006; Burgin et al., 2013). Therefore, due to the complicated behaviour of the phenomenon and its dependence on the different urban characteristics, it is essential to expand the research of it in regard of small scale cities. In view of the above, the present research focused on the study of UHI phenomenon occurring in a small city of Greece, Agrinio. The city is the hottest long-term recorded location in Greece at August and with the highest night humidity according to the relevant HNMS climatic bulletins (www.hnms.gr). To compensate these high temperatures, the urban development has been mainly based on the adaptation of passive cooling techniques like large balconies with plants and tents, water fountains, open-colored buildings of high albedo and energy consuming systems like air-conditioning in almost every house. Due to the more intense warming during summer even at a European scale, the investigation of the magnitude of UHI in the city of Agrinio could determine any further aggravation of summer heat conditions within its urban region, especially during night, and the need for developing appropriate adaptation measures in the near future. Already, a large scale PV roof development has been accomplished (14 MW from the total of 415 MW in Greece till September 2012) while the use of light paving materials, green roofs or elastomeric white paints for roofs in the city buildings is being strongly encouraged. In this frame, the city could serve as a good example of developing and adapting strategies to climate effects. In addition, the utilization of statistical models can provide useful quantitative information about the structure of the maximum UHI intensity by employing urban and meteorological parameters (Unger et al., 2001). In this context, the extent of the relation between the UHI intensity and factors like urban temperature, wind and humidity was studied for the city of Agrinio with multiple correlation and regression analyzes.

## 2. Materials and methods

Agrinio is the third biggest municipality in Western Greece, with 93,000 inhabitants, (Hellenic Statistical Authority, 2011) covering an area of 162.7 $km^2$. It is located in central-western part of Greece (latitude: 21°24′ E, longitude: 38°36′ N and elevation: 24 m) and is surrounded by four lakes and Panaitoliko mountain (northeast), influencing strongly the local climate. The weather is characterized by high temperatures, especially during summer days and high humidity nights. According to the Hellenic National Meteorological Service monthly mean temperature reaches a minimum of 8.3 °C on January and a maximum of 27.1 °C on July while mean monthly relative humidity varies from 55% to 78.5%. Table 1 shows that Agrinio is a city with one of the highest mean monthly maximum temperatures in Greece during the summer. Additionally, it often experiences extensive heat wave events (Houssos, 2009).

The city centre frame was build without a detailed urban plan and is characterized by narrow streets and medium sized buildings (4–6 floors). These characteristics combined with the absence of green leads to urban canyons effects in the city spar. Furthermore most of the buildings in the city centre were build in the decade of 70’s, with low standards of building insulation and increased needs of electricity for cooling purposes during the long warm periods of summer.

In order to evaluate the existence and the intensity of heat island in the city, a measurement station network was installed in the city spar consisting of nine mini-datalogger devices (model: Hobo ProV2) and a meteorological station. Dataloggers measured air temperatures in selected urban and suburban locations, while meteorological data

Table 2
Details and locations of the experimental stations.

| Station number | Position description and elevation | Position coordinates | Radial distance from city centre (km) | Height to width ratio | Characterization and orientation of the station |
|---|---|---|---|---|---|
| 1 University | Meteorological weather station placed on the university roof, at the south part of the city (87 m) | 38°36′45″N 21°24′55″E | 1.50 | – | Suburban |
| 2 Dokimi Airport | Placed at Dokimi, near the abandoned town airport, under populated area, few buildings, absence of traffic, much vegetation (55 m) | 38°36′52″N 21°23′16″E | 3.00 | – | Rural northwest |
| 3 Papastratou | Papastratou street, high building density, heavy traffic, highly populated area (98 m) | 38°37′48″N 21°24′30″E | 0.63 | 3.0 | Urban northwest |
| 4 Salakou | Salakou street, high building density, heavy traffic, highly populated area, no greenery (88 m) | 38°37′28″N 21°24′29″E | 0.10 | 3.0 | Urban northwest |
| 5 Gorgopotamou | Gorgopotamou street, medium building density, lot of traffic, high populated area, no greenery (83 m) | 38°37′26″N 21°24′45″E | 0.32 | 2.0 | Urban east |
| 6 Sarafi | Sarafi street, low building density, low traffic, low populated area, moderate vegetation (83 m) | 38°36′57″N 21°24′59″E | 1.20 | 1.0 | Suburban northwest |
| 7 Dimadi | Dimadi square, over the municipal parking, heavy traffic, high populated area, high building density (85 m) | 38°37′34″N 21°24′35″E | 0.19 | 2.5 | Urban northwest |
| 8 Kyprou | Kyprou street, heavy traffic, high populated area, high building density, no greenery (85 m) | 38°37′30″N 21°24′40″E | 0.14 | 2.5 | Urban west |
| 9 Souliou | Souliou street, heavy traffic, high populated area, no vegetation, high building area (88 m) | 38°37′31″N 21°24′22″E | 0.28 | 3.0 | Urban northwest |
| 10 Panaitolikou | Panaitolikou street, medium populated area, medium traffic, no vegetation, medium building area (83 m) | 38°37′36″N 21°24′54″E | 0.57 | 2.0 | Urban southwest |

were also collected for the same time period, all of them with 10 min logging. Sensors were fixed in special constructed white wooden boxes with parallel slots (like a Stevenson screen) in order to protect them from rain and solar radiation. White wooden boxes have been extensively used in similar studies (Santamouris et al., 2001, 2007; Mihalakakou et al., 2004) since they lead to accurate temperature measurements compared to radiation shields (mean difference of 0.06 °C) (Cheung Henry, 2011).

Initially, the liquid bath of the National Observatory of Athens was used to calibrate the temperature sensors. Specifications of the datalogger devices are:

- Operating range: −40 °C to 100 °C.
- Accuracy: 0.2 °C.
- Resolution: 0.02 °C.
- Stability: <0.1 °C per year.

Characteristics of the experimental stations are presented in Table 2.

The wooden boxes were placed at a height of 4–7 m above the ground. A full data set of one year was acquired from March 2010 to February 2011, after identifying the appropriate position of each sensor for a testing period of 6 months. The selection of a full year of regular and repeated measurements ensures control over random variations and contributes towards the direction of obtaining representative results (Giannaros and Melas, 2012). The same period has been extensively used in the scientific literature to study the UHI effect (Watkins et al., 2002a,b; Giannopoulou et al., 2010a,b; Kolokotsa et al., 2009; Charabi and Bakhit, 2011; Kim and Baik, 2005).To minimize the effects of solar radiation on Stevenson screens and get reliable air temperature measurements, all stations were fixed with south and south–west orientation to achieve almost the same irradiation conditions. Station 9 was not considered into the temperature data analysis due to malfunction and missing data at the six month testing period. Also, only the relative humidity and wind speed were used from station No. 1 in the statistical analysis, since a temperature sensor of different accuracy than the rest sensors was used in this station. The specific criteria used to choose the places for the sensors were:

- urban canyons geometry in urban spar (canyon height to width ratio);

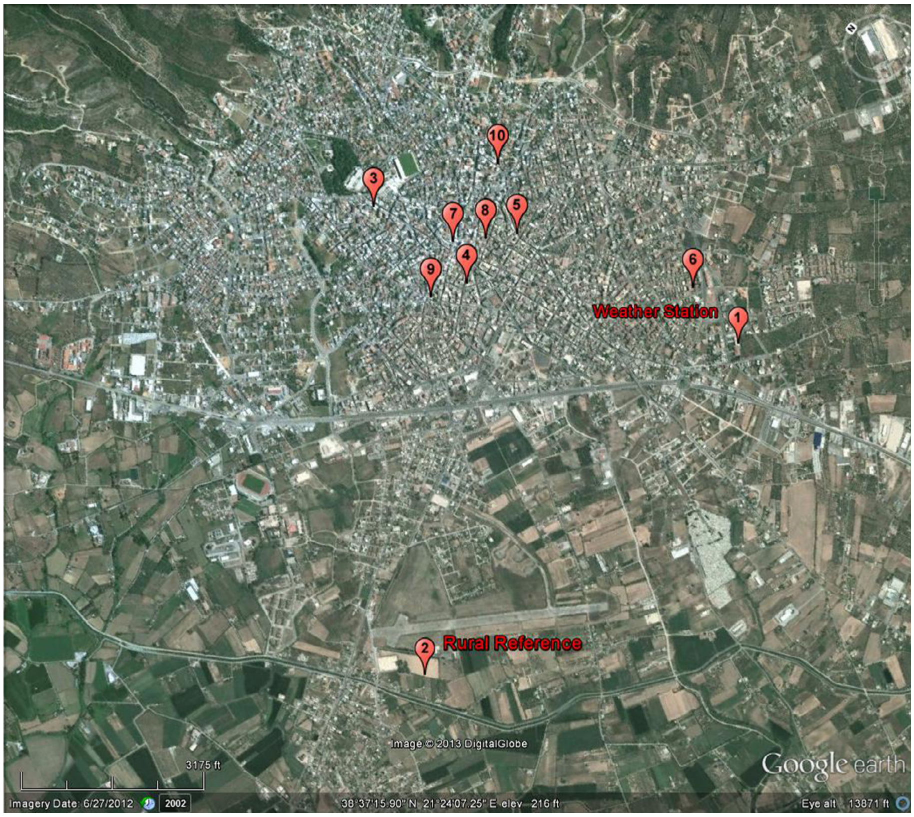


Fig. 1. Locations of all urban, suburban and rural temperature stations. (Map retrieved from Google Earth).

- places with heat of anthropogenic origin (heavy traffic flow and high populated areas);
- almost same height and orientation for all sensors;
- existence or lack of vegetation;
- different radial ranges around the city centre from 0.1 to 3 km.

In overall, seven stations were placed close to the city centre (radial distance less than 1 km from city centre), two stations in suburban areas (radial distance almost 1.5 km) and one station was placed near the city airport in a rural region outside the city spar. A map displaying the position of the stations is given in Fig. 1.

In order to determine the places where heat island is observed and specify its intensity and characteristics in the city of Agrinio, the following methodology was used: air temperature data were recorded at a 10 min interval synchronously. Every 4 months, data were collected and underwent a quality control. Hourly mean values were acquired from all dataloggers and meteorological station and were categorized according to month, season, daytime or nighttime criteria. All the temperature, relative humidity and wind speed data were analyzed as dependent and independent variables with the statistical analysis program SPSS 17.0. Mean monthly values and standard deviation for each month and each sensor were determined. Post Hoc tests (Tukey, Dunnett and two sided Games–Howell tests) were used to evaluate the difference of means between hourly mean air temperature data and to define the UHI intensity. The significance level of the tests was set at 0.05 ($\alpha = 0.05$). According to Oke (1987), the heat island intensity (UHII) is defined as the difference between the maximum urban temperature and the background rural temperature. UHII was determined by the temperature difference between each urban station ($T_u$) and the rural station 2 ($T_r$), as the reference station.

## 3. Results and discussion

### 3.1. Monthly mean temperatures around the city spar

A full year mean monthly air temperature set is presented in Fig. 2 for all stations. It can be concluded that the rural station 2 presented the lowest monthly mean air temperatures during the whole year. This is due to the area's low building density (Table 2) and the higher latent heat flux from the various vegetation species (Liu et al., 2012; Feng et al., 2010). Therefore, the station was selected as the reference temperature station ($T_r$), in order to calculate the intensity of the heat island.

In general, mean monthly maximum and minimum temperatures were observed on August and January respectively. The highest monthly mean temperature was observed in August, on station 7 (30.9 °C) and the lowest in January 2011 on station 2 (7.8 °C). According to Fig. 2, stations inside the city centre maintained higher monthly temperatures (from 0.71 °C to 2.25 °C) compared to the rural reference station, even in winter months. This

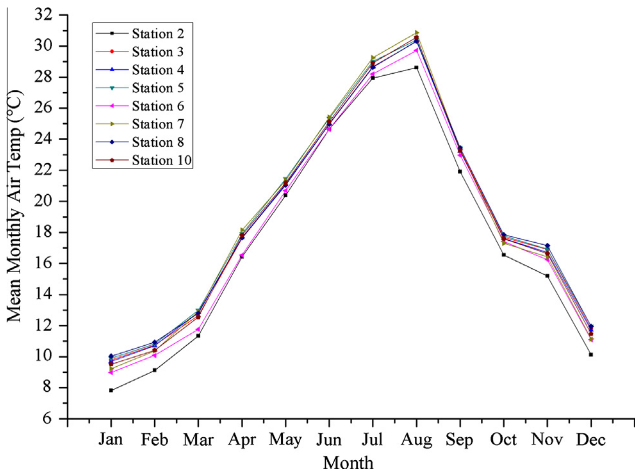


Fig. 2. Mean monthly air temperatures in each station.

finding has been observed in similar studies (Hacker et al., 2005; Memon et al., 2011) and higher air temperature in the city spar during winter can minimize the heating degree days in the urban area and might have a negative effect (Giridharan and Kolokotrni, 2009).

In order to evaluate the results in further detail, data analysis was based on the warm and cool seasons of summer and winter respectively, when the cool or warm urban environment is easier to be observed. Further datasets of diurnal and nocturnal hourly mean air temperatures were created, according to sunrise and sunset time for each month. Tables 3 and 4 summarize the mean monthly air temperature and standard deviation (s.d.) in the city of Agrinio during the daytime and nighttime for each station.

As shown in Tables 3 and 4, stations 4 (urban west) and 10 (urban east) have insignificant temperature differences (±0.5 °C) on a monthly basis. Similar small differences of up to ±0.8 °C can be noticed by checking mean temperatures of stations 3 (urban north) and 5 (urban southeast). Generally, it can be concluded that there was a homogeneity of mean monthly midtown temperature (stations No. 3, 4, 5, 7, 8, 10) with the small temperature variations to be caused by the specific conditions of each place. This homogeneity was maintained in both diurnal and nocturnal conditions. In addition, the suburban station 6 presented lower air temperatures than all other urban stations since it is situated in a low building density environment and less populated area with short burst of wind coming from the mainland.

### 3.2. Characteristics of UHI levels during summer

The UHII was calculated from the difference between the rural reference in the city airport (station 2) and different stations close to the city centre (characterized as urban or suburban stations in Table 2).

Estimated differences from the observed mean monthly air temperatures during summer 2010, show that heat island in Agrinio is mainly a nocturnal effect (Table 5). The monthly mean heat island intensity reached its maximum value of 3.8 °C during nights of August 2010 at station 7, but values up to 5.6 °C, based on mean hourly temperatures, were also observed. The results of the maximum intensity agree with the value calculated from the n relation given by Oke (1973), i.e.

$$\Delta T_{\text{u–r(max)}} = 2.01 * \log P - 4.06 \tag{1}$$

Indeed, an UHI intensity of 5.9 °C is determined from Eq. (1) for the population of Agrinio.

Intensity levels at station 7 are due to the anthropogenic heat released from the cars along all day at this crowded area station (Kimura and Takahashi, 1991; Papanastasiou and Kittas, 2011). In addition, the area is fully covered by large amounts of concrete forming an environment of high sensible heat storage, which releases high amounts of infrared radiation during night. Monthly UHII for the other stations of the same period varied between 2.5 °C and 3.2 °C, proving that summer nights are the most "cooling spending" period of the year in the city of Agrinio. The same result is shown in Fig. 3, where the plots of frequency distribution of the intensity for four different central-town stations during the nights of summer 2010, reveal that the city centre was "warmer" than the rural reference location for more than 99% of night duration. In Fig. 4, the night temperature distributions for the city centre at August compared to the rural reference station are presented. A remarkable shift of over 26 °C on city temperature is observed for most of summer nights, leading to a substantial increase of the cooling energy demands that is mainly provided by air-conditioning all night long.

In contrast, many stations proved to be "cooler" than the reference station during the daytime of June and July. This result has also been reported from Montavez et al. (2000) and Hafner and Kiddler (1999) and agrees with similar past research of Watkins et al. (2002a) for London and Carmen Moreno-Garcia (1993) for Barcelona.

Table 3
Diurnal mean monthly air temperatures and s.d. for all stations (°C).

| Season | Month | Station 2 | Station 3 | Station 4 | Station 5 | Station 6 | Station 7 | Station 8 | Station 10 |
|---|---|---|---|---|---|---|---|---|---|
| Summer 2010 | June | 27.71 ± 4.24 | 27.03 ± 4.48 | 26.94 ± 4.50 | 27.81 ± 4.19 | 26.63 ± 4.46 | 27.39 ± 4.61 | 27.12 ± 4.63 | 27.2 ± 4.39 |
| | July | 31.26 ± 3.34 | 30.83 ± 3.68 | 30.81 ± 3.68 | 31.7 ± 3.10 | 30.35 ± 3.74 | 31.38 ± 3.44 | 31.02 ± 3.91 | 31.22 ± 3.39 |
| | August | 32.01 ± 3.57 | 32.61 ± 3.90 | 32.66 ± 3.82 | 33.07 ± 3.28 | 32.09 ± 4.00 | 33.13 ± 3.62 | 32.91 ± 4.20 | 33.08 ± 3.90 |
| Winter 2010–2011 | December | 11.64 ± 4.62 | 13.08 ± 4.46 | 12.66 ± 4.33 | 13.27 ± 4.45 | 12.34 ± 4.42 | 12.17 ± 4.34 | 13.5 ± 4.68 | 12.81 ± 4.49 |
| | January | 9.68 ± 3.22 | 11.32 ± 3.00 | 10.81 ± 2.62 | 11.51 ± 2.99 | 10.58 ± 3.02 | 10.5 ± 2.70 | 11.94 ± 3.69 | 11.11 ± 3.51 |
| | February | 10.98 ± 3.79 | 12.33 ± 3.44 | 11.96 ± 3.00 | 12.46 ± 3.52 | 11.74 ± 3.57 | 11.81 ± 3.17 | 12.71 ± 3.97 | 12.06 ± 3.87 |

Table 4
Nocturnal mean monthly air temperatures and s.d. for all stations (°C).

| Season | Month | Station 2 | Station 3 | Station 4 | Station 5 | Station 6 | Station 7 | Station 8 | Station 10 |
|---|---|---|---|---|---|---|---|---|---|
| Summer 2010 | June | 20.37 ± 2.94 | 22.17 ± 3.11 | 22.25 ± 3.06 | 21.91 ± 3.13 | 21.86 ± 3.10 | 22.67 ± 3.22 | 21.94 ± 3.11 | 22.2 ± 3.10 |
| | July | 23.29 ± 2.37 | 25.62 ± 2.27 | 25.63 ± 2.33 | 25.22 ± 2.44 | 25.2 ± 2.35 | 26.26 ± 2.32 | 25.29 ± 2.39 | 25.69 ± 2.39 |
| | August | 23.9 ± 2.41 | 27.08 ± 2.12 | 27.06 ± 2.18 | 26.66 ± 2.21 | 26.44 ± 2.23 | 27.72 ± 2.13 | 26.73 ± 2.25 | 27.06 ± 2.24 |
| Winter 2010–2011 | December | 9.03 ± 4.77 | 10.91 ± 4.39 | 11.07 ± 4.26 | 11.02 ± 4.32 | 10.22 ± 4.39 | 10.4 ± 4.24 | 10.82 ± 4.40 | 10.54 ± 4.21 |
| | January | 6.49 ± 3.10 | 8.69 ± 2.45 | 8.9 ± 2.33 | 8.76 ± 2.42 | 7.86 ± 2.53 | 8.32 ± 2.35 | 8.69 ± 2.48 | 8.38 ± 2.40 |
| | February | 7.55 ± 2.96 | 9.38 ± 2.38 | 9.66 ± 2.30 | 9.45 ± 2.41 | 8.68 ± 2.52 | 9.18 ± 2.34 | 9.42 ± 2.46 | 9.10 ± 2.44 |

Table 5
Mean monthly UHI intensity for all stations during summer. Minus and plus corresponds to cool and heat island periods respectively.

| Month | Station 3 | Station 4 | Station 5 | Station 6 | Station 7 | Station 8 | Station 10 |
|---|---|---|---|---|---|---|---|
| *Summer period* | | | | | | | |
| June day | −0.679 | −0.774 | 0.090 | −1.080 | −0.319 | −0.589 | −0.508 |
| June night | 1.803 | 1.877 | 1.536 | 1.487 | 2.297 | 1.587 | 1.832 |
| July day | −0.430 | −0.454 | 0.436 | −0.912 | 0.118 | −0.239 | −0.044 |
| July night | 2.335 | 2.342 | 1.929 | 1.917 | 2.974 | 2.001 | 2.407 |
| August day | 0.601 | 0.647 | 1.062 | 0.077 | 1.122 | 0.903 | 1.066 |
| August night | 3.187 | 3.161 | 2.767 | 2.549 | 3.826 | 2.830 | 3.161 |

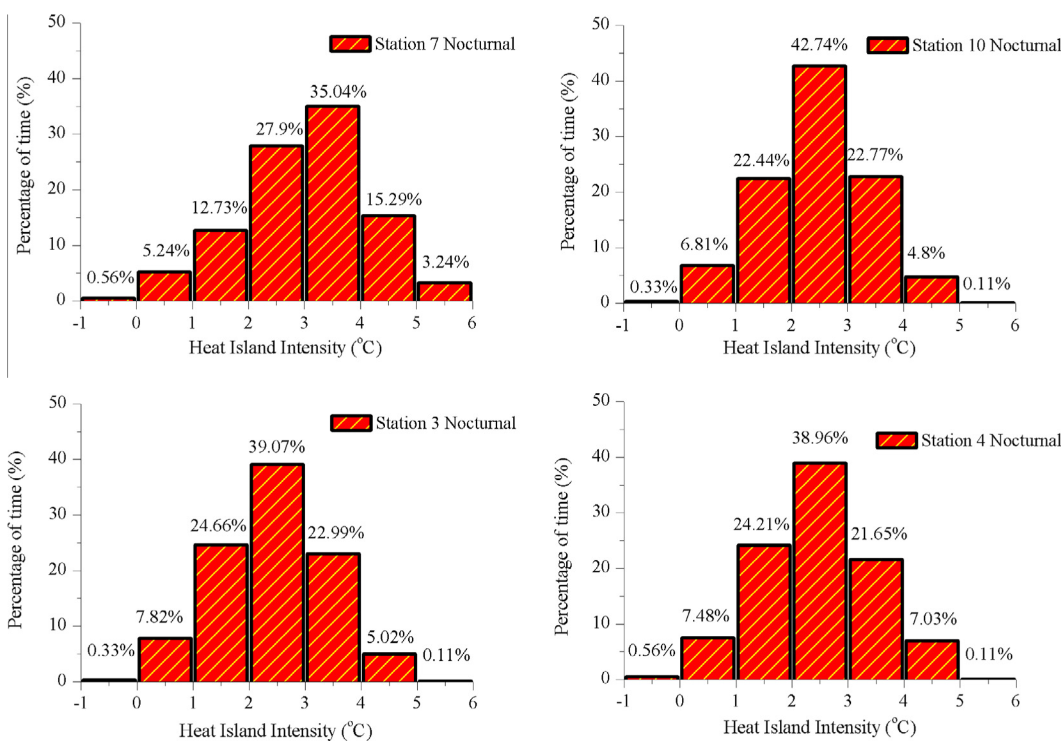


Fig. 3. Frequency distribution of nighttime heat island intensity during summer of 2010 in Agrinio for four different urban stations (refers to mean hourly temperature values).

According to the frequency distribution histograms presented in Fig. 5 for 4 central-town stations, there is a cool island in the city centre which often exceeds 50% of daytime during summer. This “Urban Cool Island (UCI)” or the so called “negative UHI” can be attributed to the shading effect of buildings, the reduction of solar radiation in the city spar due to air pollutants and the higher urban heat storage (Memon et al., 2009).

The mean hourly evolution for 24 h of cool and heat island effect for all stations during the summer is shown in Fig. 6. It is clear that a cool island was shaped early in the morning (7 a.m.) and turned into a heat island in the afternoon (12 a.m.) for most of the stations. An explanation to this process could be the high thermal capacity of the urban environment due to the used construction materials. During the first hours after sunrise, city environment

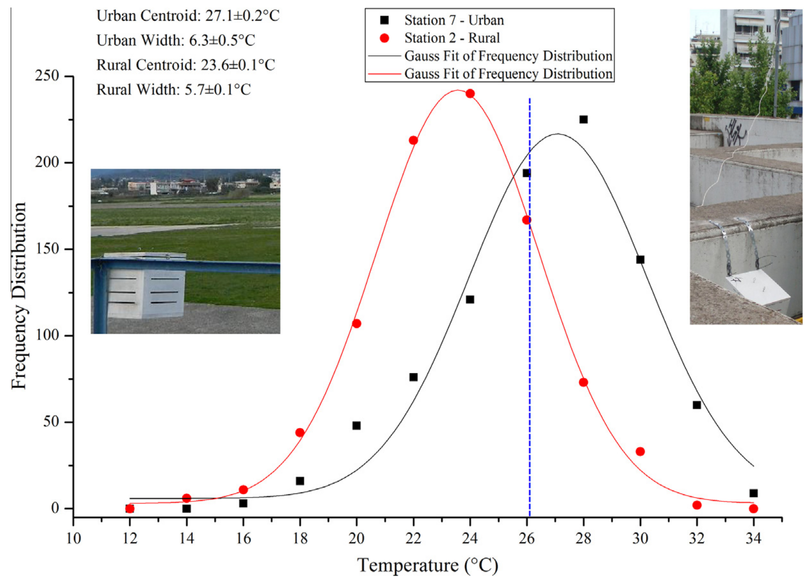


Fig. 4. Urban and rural frequency distribution and Gaussian fit of night temperature.

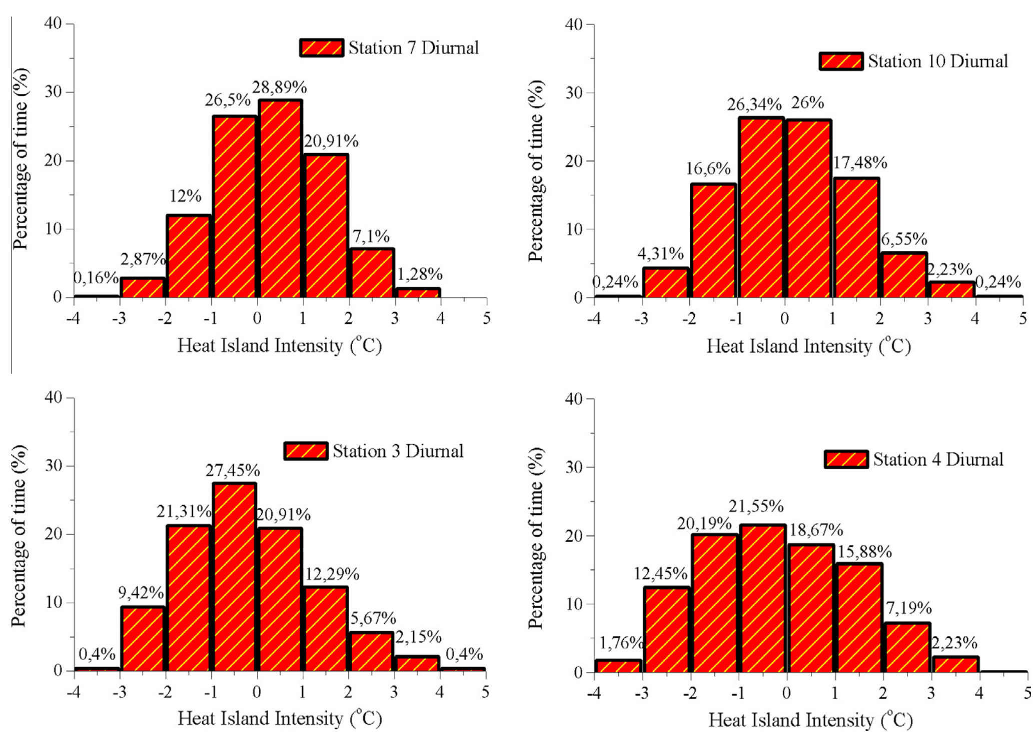


Fig. 5. Frequency distribution of daytime heat island intensity during summer of 2010 in Agrinio for four different urban stations (refers to mean hourly temperature values).

reacts slowly to the solar radiation and absorbs energy at lower rates compared to rural environment (Oke, 1987; Hafner and Kiddler, 1999; Pena, 2008). Thus, an energy propagation time lag between city and country environment is created. Also large shaded areas in city centre can be considered as a key factor for urban heat sink formation during the first hours of the day (Oke, 1987; Nickol, 1998; and Voogt, 2002). The cause of this fact is the oblique solar elevation angle that interacts with the buildings and reduces the intercepted and stored energy by their surfaces. After 18:00 till early in the morning (6:00 a.m.), city centre firmly maintains higher temperatures than the rural environment indicating that Agrinio heat island is a prevailing nocturnal phenomenon.

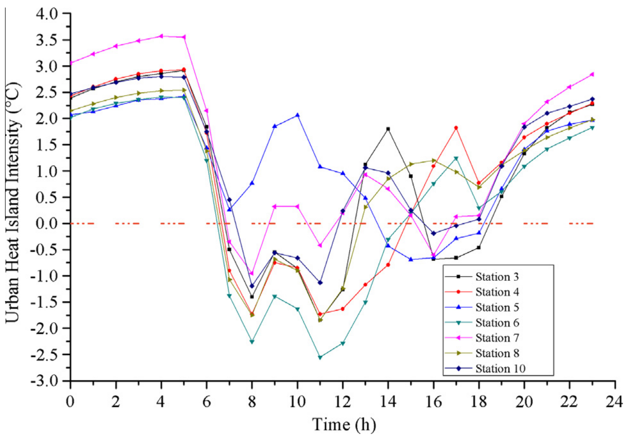


Fig. 6. 24 h time evolution of urban heat island intensity for all station during the summer.

### 3.3. Characteristics of heat island during the seasons of winter and summer

Extensive research in the past has been mainly concentrated on the UHI evolution during summer and its negative consequences, as a contributor to the increased cooling energy demands of the cities (Giannopoulou et al., 2010a,b; Kolokotsa et al., 2009;Papanastasiou and Kittas, 2011). However, the influence of the effect in winter is also important since it may reduce the heating energy needs. Indeed, monthly UHII reached values of 2.4 °C higher at station 4 than station 2, during the nights of January 2011, when the lowest temperatures in the city are observed and the needs for heating are increased (Table 6).

The histograms of mean hourly temperature differences for four different urban stations in Figs. 7 and 8, reveal that during winter the heat island effect was strongly present at both night and day, while the UCI (observed during summer) almost disappeared. In particular, the effect during winter nights followed very similar behavior like in summer nights. City remained warmer than country all night long, but UHI intensity levels were lower and range from 1 °C to 4 °C.

During daytime, the UCI effect was observed in a small percentage of measurements (about 10%), implying a modification of the effect compared to the summer-time. A high percentage of measurements (about 60%) correspond to small heat island intensities (1–2 °C) while higher intensities were sparsely noted. By translating these results, a rewarding reduction on heating load of the city could be expected, proving that the UHI effect can act positively for city residents during winter time by reducing the heating degree days.

The enhanced UHI intensities during summer compared to winter period, can be attributed mostly to the amounts of incoming solar radiation which are significantly larger at this part of the year. Additionally, the synoptic weather conditions prevailing over Greece during the warm period affect the UHI magnitude, since the Azores subtropical anticyclone extends over the Mediterranean basin resulting in very stable atmospheric conditions with clear sky (Kassomenos and Katsoulis, 2006). On the other hand, additional anthropogenic activity such as central heating contributes to maintaining the UHI values during winter.

In Fig. 9, the hourly mean 24-h evolution for the UHI intensity is presented for each station. It can be concluded that heat island is a dominating night time phenomenon similar to the observation in the summer time, in Agrinion city.

### 3.4. Hourly heat island intensities and urban station temperatures

The relative temperature differences between mean hourly data of reference and urban stations are plotted as a function of the temperature of the urban station in Figs. 10–13. The plotted data refer to four different time periods (summer day, summer night, winter day and winter night). During summer days, mean hourly temperature differences reached values as high as 5.0 °C, while higher heat island intensities were observed for city temperatures greater than 35.0 °C (Fig. 10). Heat island levels proved to be lower for areas characterized as suburban (e.g. station 6) reaching in most of the cases, a maximum of 2.0 °C and even at high temperatures. During nights of summer, intensity levels become higher and the UCI effects that are present during day, almost disappear (Fig. 11). Intensity levels remained high even at low city air temperatures (e.g. 5.0 °C UHII for 25.0 °C air temperature at station 4). This fact can justify the characterization of cities as energy dumps and proves that heat island becomes a crucial problem in the city spar during summer nights.

During winter days, an extensive scattering of data was evident with intense peaks at 7–8 °C (stations 8, 3

Table 6
Mean monthly UHI intensity for all stations during winter (°C).

| Month | Station 3 | Station 4 | Station 5 | Station 6 | Station 7 | Station 8 | Station 10 |
|---|---|---|---|---|---|---|---|
| *Winter Period* | | | | | | | |
| December day | 1.441 | 1.023 | 1.633 | 0.696 | 0.525 | 1.858 | 1.167 |
| December night | 1.879 | 2.041 | 1.988 | 1.187 | 1.366 | 1.788 | 1.510 |
| January day | 1.641 | 1.130 | 1.834 | 0.908 | 0.821 | 2.267 | 1.429 |
| January night | 2.203 | 2.410 | 2.268 | 1.369 | 1.835 | 2.199 | 1.885 |
| February day | 1.350 | 0.970 | 1.470 | 0.752 | 0.824 | 1.728 | 1.080 |
| February night | 1.832 | 2.110 | 1.896 | 1.133 | 1.630 | 1.873 | 1.547 |

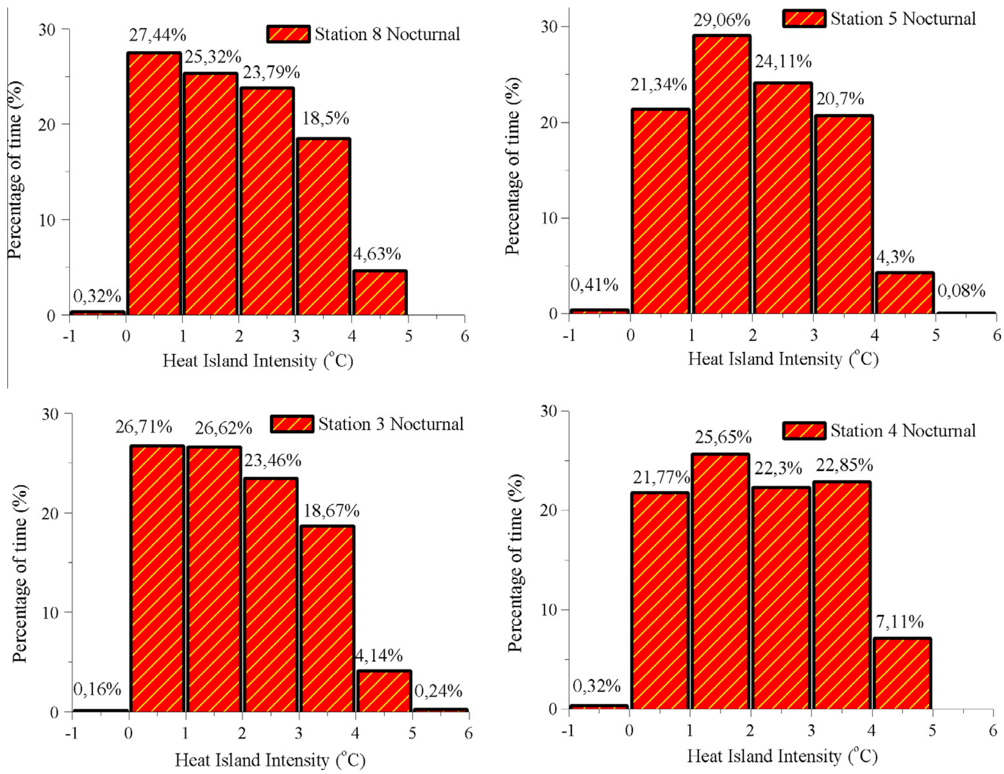


Fig. 7. Frequency distribution of the nighttime heat island intensity during winter of 2010–2011 in Agrinio for four different urban stations (refers to mean hourly temperature values).

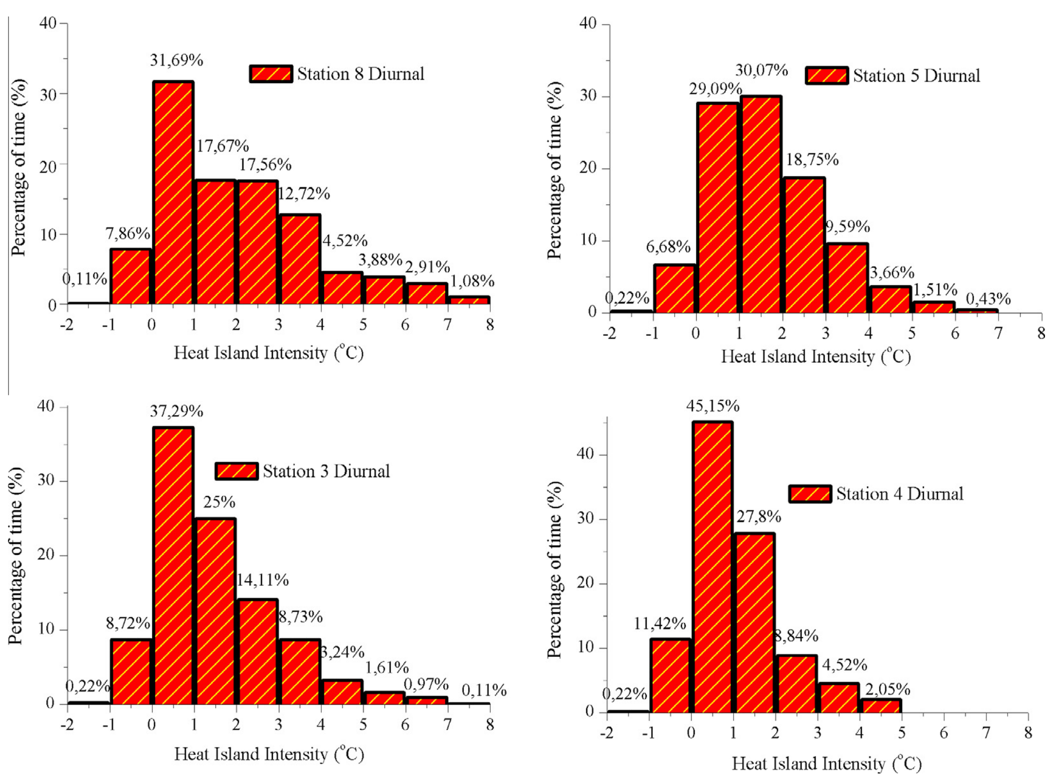


Fig. 8. Frequency distribution of the daytime heat island intensity during winter of 2010–2011 in Agrinio for four different urban stations (refers to mean hourly temperature values).

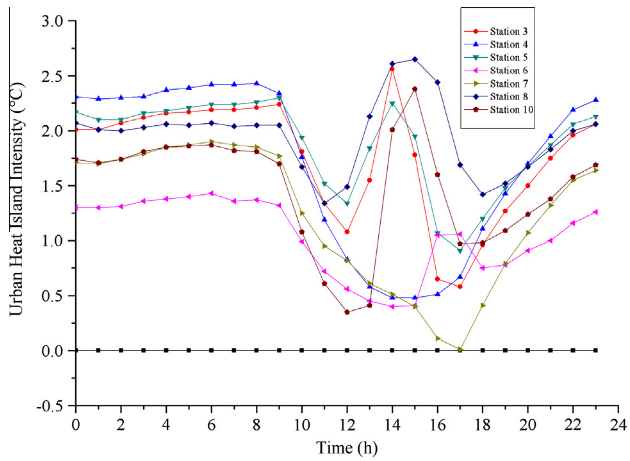


Fig. 9. 24 h time evolution of urban heat island intensity for all stations during winter.

and 10) (Fig. 12). According to the corresponding meteorological data, some of these were related to the high humidity levels, rain showers (Watkins et al., 2002a) and wind calm. But others proved to be real heat islands that are shaped from the individual area's buildings and characteristics.

In winter nights, city centre remains 1.0–5.0 °C warmer than the rural reference area even when temperature levels in the city spar followed below 10.0 °C (Fig. 13).

### 3.5. Impact of environmental variables on the heat island intensity during summer

Wind speed patterns in the urban environment is an important parameter for the heat island shape and intensity, since small differences in topography of city spar can cause irregular air flows and block city cooling through building surface convection. In this context, local characteristics of each area like building geometry, street width and greenery and existence of street canyons, can strongly affect the microclimate (Santamouris et al., 2001; Giannopoulou et al., 2010a,b; Bady et al., 2011). In the present study, all wind speed data were recorded close to the university area (mark 1 in Fig. 1). Since this area is categorized as suburban, wind speed values inside the city spar should range at even lower levels. Wind speed was grouped into four categories. Such categorization was necessary in order to have sufficient statistical sample of measurements for all the wind speed ranges:

- Category 1: wind speeds of less than 2.5 km/h, representing almost 50% of total recorded samples (1063 samples). This speed range is the most often observed case for the city of Agrinio.
- Category 2: wind speeds between 2.5 and 5 km/h (432 samples).
- Category 3: wind speeds between 5 and 7.5 km/h (340 samples).
- Category 4: wind speeds over 7.5 km/h (315 samples).

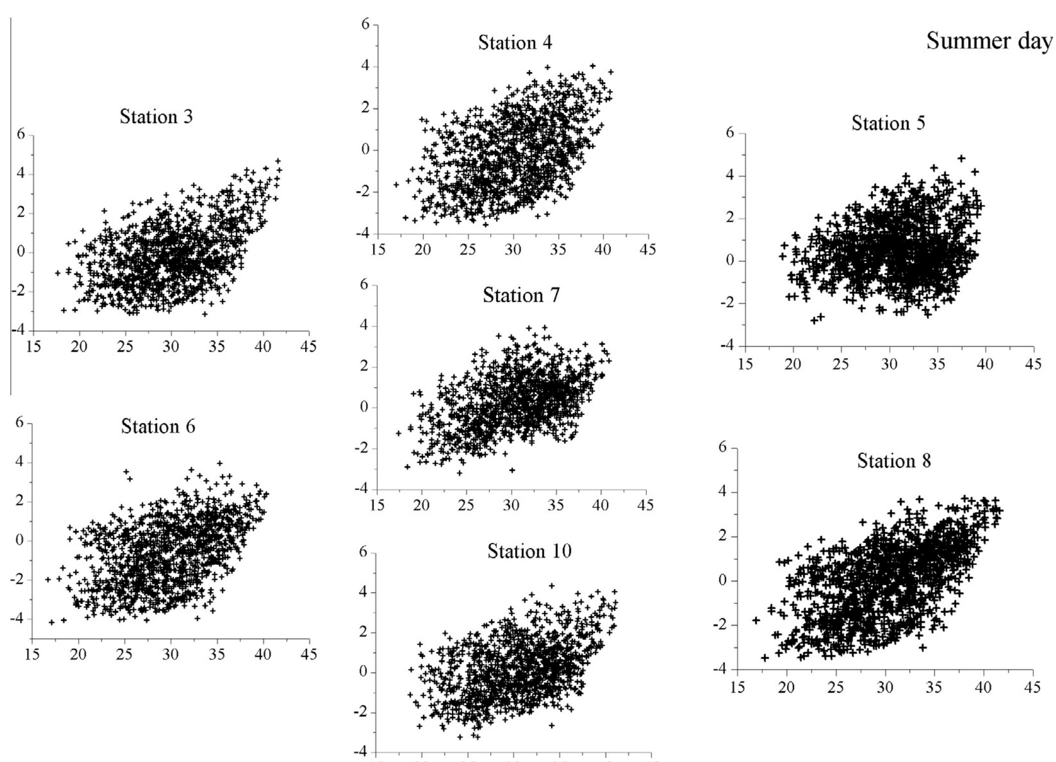


Fig. 10. Scatterplot of temperature difference between urban stations and the reference one (UHI intensity) as a function of the absolute temperature of the urban station during summer days.

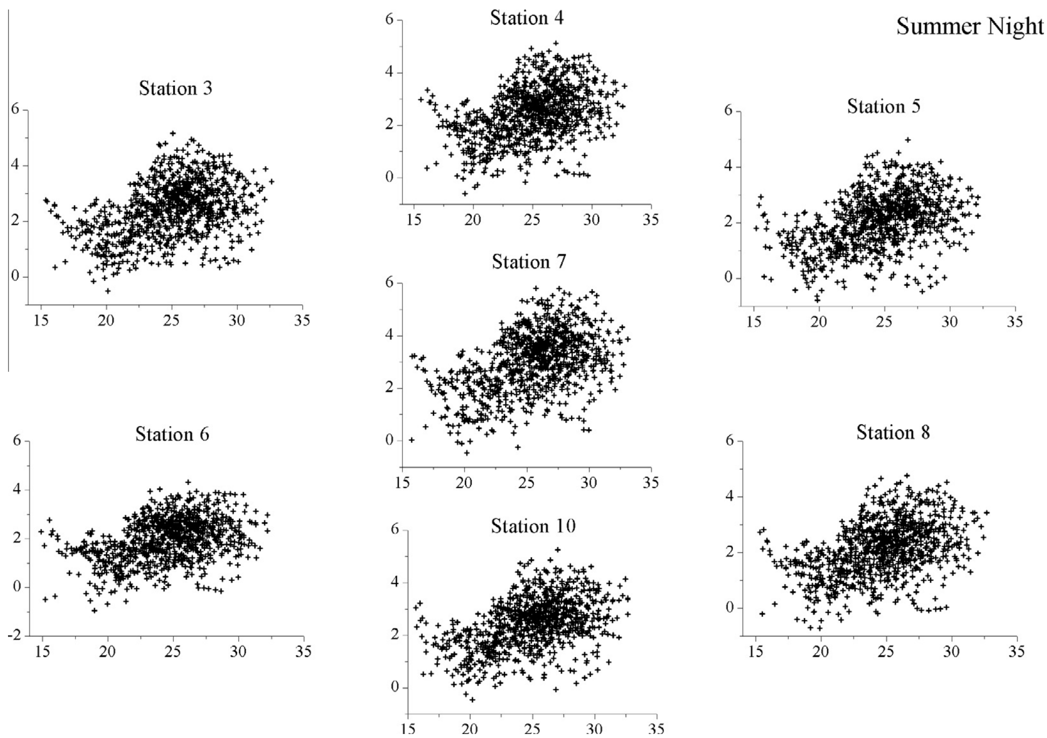


Fig. 11. Scatterplot of temperature difference between urban stations and the reference one (UHI intensity) as a function of the absolute temperature of the urban station during summer nights.

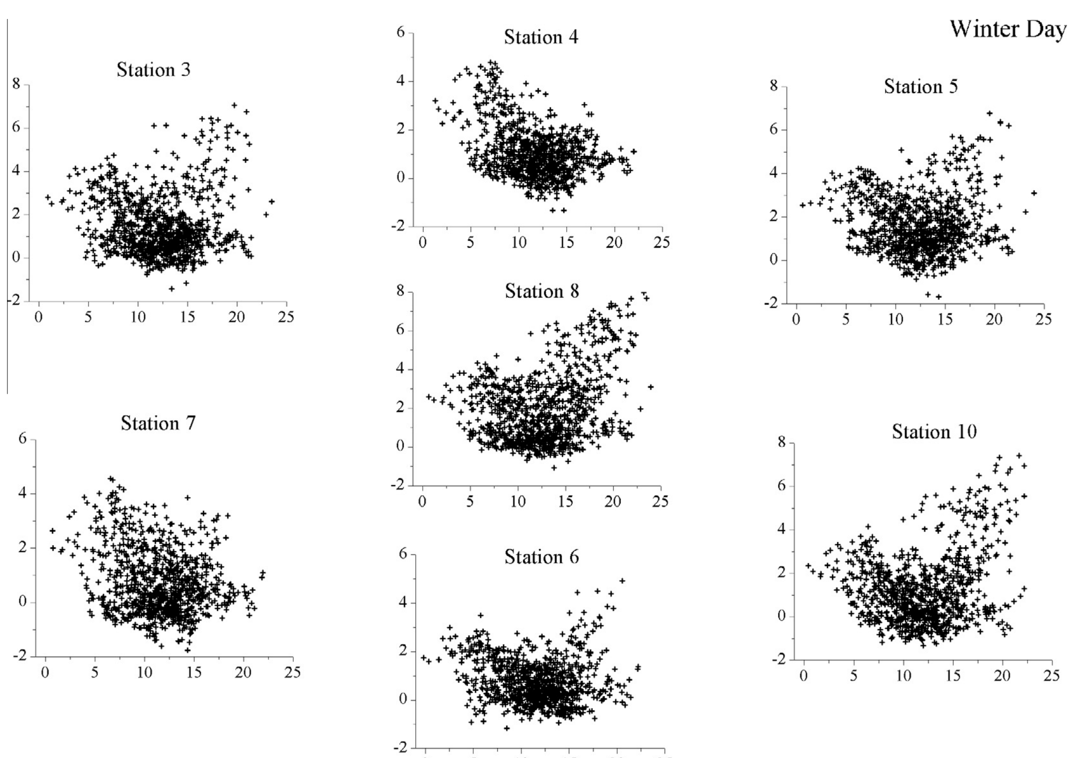


Fig. 12. Scatterplot of temperature difference between urban stations and the reference one (UHI intensity) as a function of the absolute temperature of the urban station during winter days.

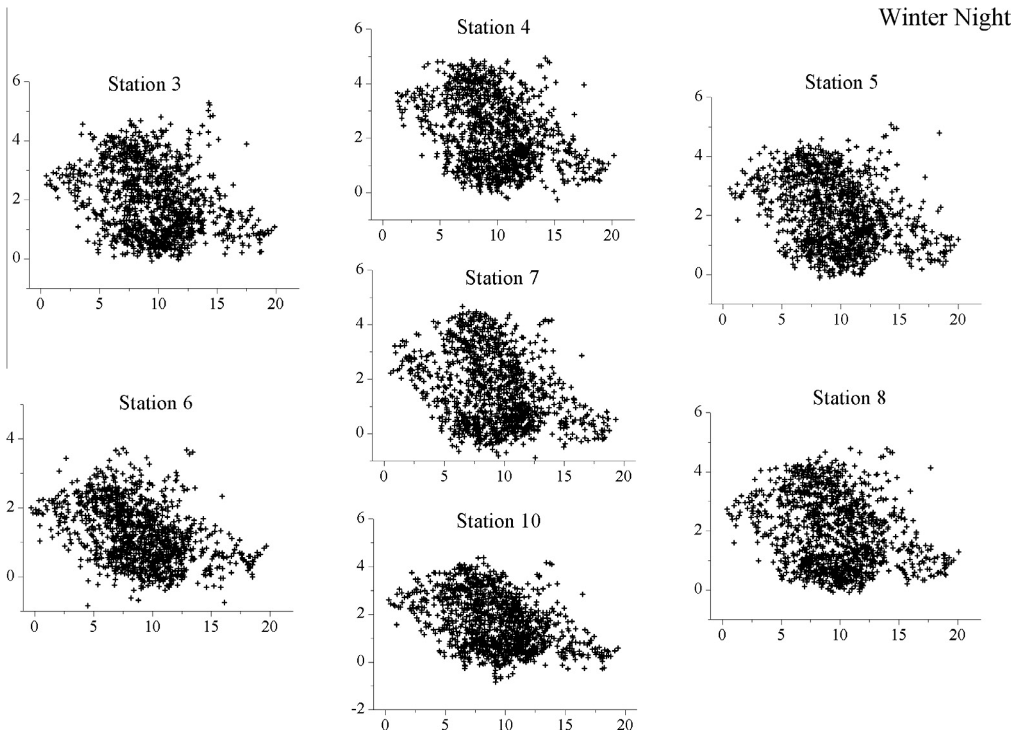


Fig. 13. Scatterplot of temperature difference between urban stations and the reference one (UHI intensity as a function of the absolute temperature of the urban station during winter nights.

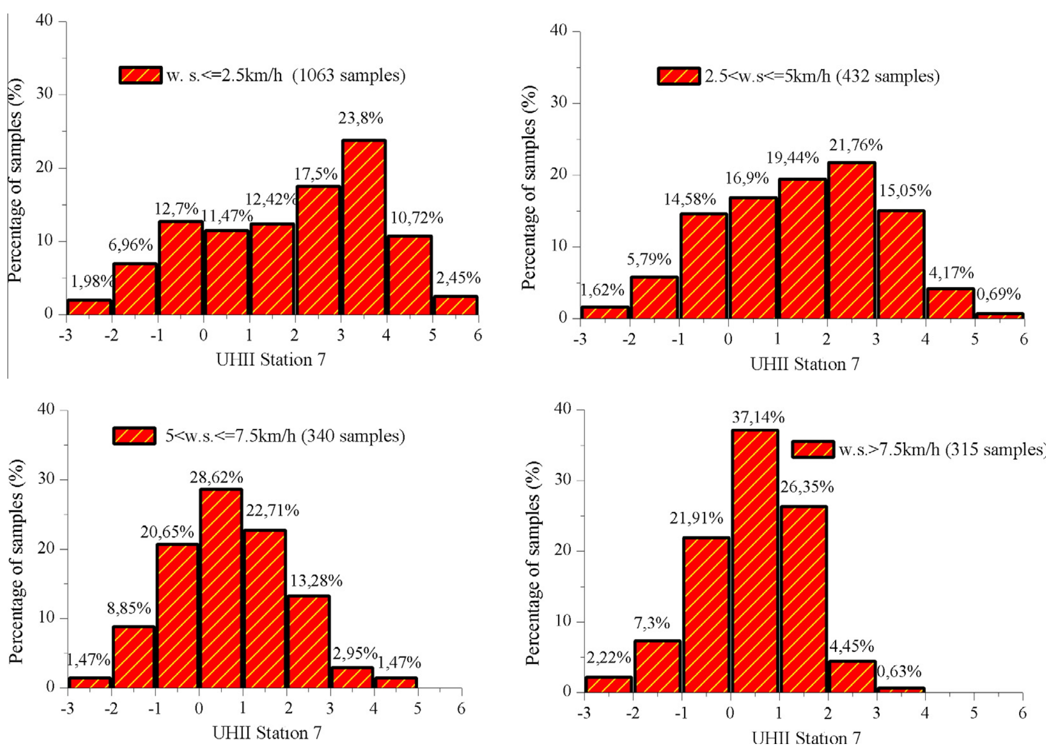


Fig. 14. UHII histogram and wind speed impact during the summer on station 7.

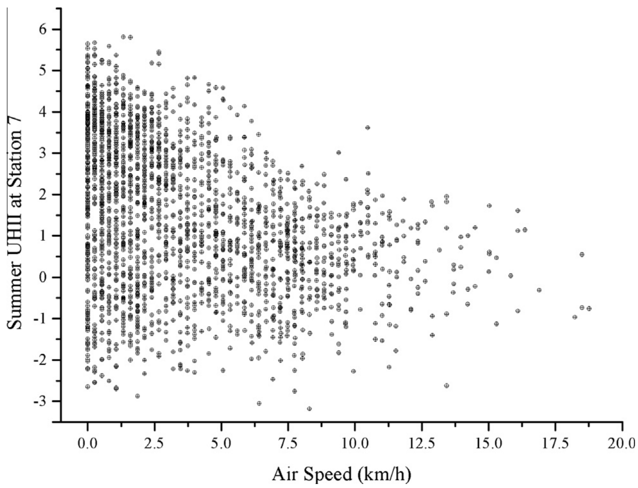


Fig. 15. Scatter plot illustrating the association of the UHI intensity and wind speed.

The correlation between the wind speed and the heat island intensity on station 7 at the city centre is investigated in Figs. 14 and 15. Wind affects strongly the intensity of the heat island by producing different cooling rates between urban and rural areas. At wind speed levels of the first category (wind speed <2.5 km/h) almost 52% of $\Delta T_{U-R}$ values vary between 2 and 5 °C, implying that calm and low wind speeds contribute to strong UHI intensities. This percentage (e.g. heat island levels between 2 and 5 °C), reduces about 11% at wind speeds of category 2. Intensity levels reduce strongly when the wind in the city reaches speeds higher than 5 km/h (categories 3 and 4). At these speeds, 72% and 85% of UHII measurement samples varied between −1 and 2 °C, for wind categories 3 and 4 respectively. Also for these two categories, the frequency distribution of the UCI in the city increased by almost 10% (Fig. 14). It can be concluded from these results that the UHI intensity magnitude is significantly affected by the velocity of local airmass and strong wind can effectively cool small cities. High UHI intensities tend to be highly correlated with conditions of low wind speed or wind calm. Wind speeds over 5 km/h, refreshes air masses in the city spar and offer a substantial cooling effect, associated with low heat island levels and even cool islands occasionally. The observation of the correlation between wind speed and the UHI intensity are in agreement with similar studies (Morris and Simmonds, 2001; Santamouris et al., 2001).

In Fig. 15, the scatterplot of the daily UHI values (station 7) against the corresponding wind speeds during summer of 2010, presents their relationship described previously. According to Oke (1970), every town has a critical wind speed necessary to eliminate the heat island effect which depends on the size of the population. Based in Fig. 15, the corresponding air speed threshold for the city of Agrinio, is close to the value of 7.5 km/h during the summer period. Over this urban air speed, the majority of the heat island intensity measurement lays at values less than 2 °C and urban–rural temperature difference tends to be minimal.

Furthermore, the relation between the UHII and factors like urban temperature and relative humidity was investigated. The Pearson correlation coefficient was used to test the strength of linear dependence between the upper variables. Regarding the humidity-UHII dependence, a negative coefficient of −0.46 and −0.48 was calculated for summer nights and days, respectively. This moderate to low negative correlation shows that reduced evaporation levels in urban environment increase heat storage during the day. This stored energy is released back to the atmosphere during night through the higher infrared radiation. Also, a positive factor of 0.46 during night or day – was found in regard of the correlation of the UHII and urban environment temperature. Although moderate and low, this value indicates that high UHII levels in city spar may be also affected by the heat wave periods and points out the necessity of UHI mitigation strategies adaptation in the future community plan.

## 4. Heating–cooling energy needs and future trends

In order to evaluate the requirements for the excess cooling energy in summer and the reduction of heating energy during winter due to the heat island effect, degree-hours calculation method was used. Temperature measurements for the study period (March 2010 to February 2011) from an urban (station 7) and a rural station (station 2) were used. The degree-hours method for shorter periods than a year has been widely used for many countries in Europe (Bolatturk, 2008). In this work, a base temperature of 18 °C for the heating period during winter months and 27 °C for the cooling period during summer were used for the calculation of the degree hours and the heating and cooling energy requirements, (TCG, 2010). On a monthly basis, the total number of heating degree hours is defined by the following formula (Papakostas and Kyriakis, 2005):

$$HDH(t_{\text{bal}}) = \sum_{j=1}^{N} (t_{\text{bal}} - \bar{t}_o)$$

where $\bar{t}_o$ is the hourly mean outdoor temperature of the station, $t_{\text{bal}}$ is the base temperature and N the number of hours within a month. The corresponding formula for the total number of cooling degree hours is:

$$CDH(t_{\text{bal}}) = \sum_{j=1}^{N} (\bar{t}_o - t_{\text{bal}})$$

Only positive values are summed in both formulas.

According to Giannakopoulos et al. (2009), a 2 °C global warming is most likely to occur during spring and winter in the Mediterranean region, while it reaches 4 °C during summer. Tolika et al. (2008) estimated future changes in extreme temperature conditions during the future period of 2070–2100 for many Greek locations and

Table 7
Cooling and heating degree hours for the urban and rural temperature station.

| Period of the year | Month | Cooling and heating degree hours | | | | Energy needs variation of the city centre in comparison to the rural area | |
|---|---|---|---|---|---|---|---|
| | | Current trend | | Future trend-2060 scenario | | | |
| | | City centre | Rural area | City centre | Rural area | Current (%) | Future (%) |
| Winter heating degree hours | December | 5160 | 5906 | 4476 (−13.2%) | 5215 (−11.7%) | −12.6 | −14.2 |
| | January | 6525 | 7577 | 5781 (−11.4%) | 6833 (−9.8%) | −13.9 | −15.4 |
| | February | 5117 | 5965 | 4449 (−13.1%) | 5293 (−11.3%) | −14.2 | −15.9 |
| Summer cooling degree hours | June | 1183 | 1137 | 1508 (+27.5%) | 1433 (+26%) | +4.0 | +5.2 |
| | July | 2707 | 2372 | 3304 (+22.1%) | 2841 (+19.8%) | +14.1 | +16.3 |
| | August | 3421 | 2510 | 4054 (+18.5%) | 2969 (+18.3%) | +36.3 | +36.5 |

predicted that the extreme temperatures are going to increase in the future period (around 1 °C for Agrinio area for most of the applied models). According to the work of Zanis et al., 2009, temperature future projections over Greece for the period 2071–2100, considering nine Regional Climate Models (RCMs) under the A2 emission scenario, give a mean increase of 3.4 °C in the air temperature for winter and 4.5 °C for summer with the changes being larger in continental areas. In order to evaluate the future energy needs in a future climate scenario, a 1 °C global warming was assumed as a conservative scenario during summer and winter for the next 50 years. In this, the future heating and cooling degree hours calculated from the current air temperature measurements in urban and rural environment are presented in Table 7.

By the variation of the current energy needs, the UHI effect resulted in reducing the heating degree hours during the winter in the city centre compared to the rural area (12.63–14.22% reduction). During summer, an increase in the cooling degree hours of the city is observed, compared to the rural, with a maximum of 36.3% during August 2010.

By considering a future trend of 1.0 °C temperature increase during summer and winter, the heating energy needs are reduced, while the cooling energy needs are increased in both rural and urban sites. In the city centre, a decrease from 11.4% and up to 13.2% is noticed on the heating degree hours, while the cooling degree hours are increased from 18.5% to 27.6%. In the rural area, a decrease of 9.8% to 11.7% is observed on the heating degree hours, while cooling degree hours are increased from 18.3% to 26.0%.

These results indicate that future energy needs are expected to be dramatically increased and points out the urgent need of countermeasures to mitigate the UHI effect.

## 5. Conclusions

The heat island effect and its characteristics in a hot small city of Western Greece have been investigated by using a local grid of nine temperature microdataloggers and a meteorological station. Results showed that the effect was a night dominating phenomenon, while a cool island effect was observed early in the morning in many temperature stations in the city spar. A maximum mean monthly UHI intensity of 3.8 °C was observed at station 7 during nights of August 2010 while instantaneous hourly intensities reached even higher values and up to 5.6 °C. During winter, about 60% of the measurements were found to refer to small heat island intensities, a result that could have a positive impact on the heating load of the city. The relationship between the UHI intensity and local airflow was also investigated using measurements of wind speed. High UHI intensities are associated with low wind speed or wind calm conditions, whereas for wind speeds higher than 7.5 km/h, heat island intensity is minimum (<2 °C) and even tends to be eliminated. Future trends show that the cooling degree hours in cities like Agrinio are expected to be highly increased. Therefore, according to the results of the present study, the presence of the UHI in cities with hot summers results in nights of exceptional high temperatures and long duration with a direct influence in energy consumption and life quality and the need for urgent remediation and adaptation actions.

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