

Maximum urban heat island intensity in a medium-sized coastal Mediterranean city

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Abstract This paper studies the maximum intensity of the urban heat island (UHI) that develops in Volos urban area, a medium-sized coastal city in central Greece. The maximum temperature difference between the city center and a suburb is 3.4°C and 3.1°C during winter and summer, respectively, while during both seasons the average maximum UHI intensity is 2.0°C. The UHI usually starts developing after sunset during both seasons. It could be attributed to the different nocturnal radiative cooling rate and to the different anthropogenic heat emission rate that are observed at the city center and at the suburb, as well as to meteorological conditions. The analysis reveals that during both seasons the daily maximum hourly (DMH) UHI intensity is positively correlated with solar radiation and with previous day's maximum hourly UHI intensity and negatively correlated with wind speed. It is also negatively correlated with relative humidity during winter but positively correlated with it during summer. This difference could be attributed to the different mechanisms that mainly drive humidity levels (i.e., evaporation in winter and sea breeze (SB) in summer). Moreover, it is found that SB development

triggers a delay in UHI formation in summer. The impact of atmospheric pollution on maximum UHI intensity is also examined. An increase in PM10 concentration is associated with an increase in maximum UHI intensity during winter and with a decrease during summer. The impact of PM10 on UHI is caused by the attenuation of the incoming and the outgoing radiation. Additionally, this study shows that the weekly cycle of the city activities induces a weekly variation in maximum UHI intensity levels. The weekly range of DMH UHI intensity is not very large, being more pronounced during winter (0.4°C). Moreover, a first attempt is made to predict the DMH UHI intensity by applying regression models, whose success is rather promising.

1 Introduction

Temperature levels are higher in the center of a city than in its suburbs due to the urban heat island (UHI) phenomenon. The UHI intensity is defined as the temperature difference between the urban area and its surroundings. It is usually determined by exploiting air temperature measurements recorded by weather stations or surface temperature data extracted from satellite images. Other methods include analysis of measurements collected by mobile stations and model application. Memon et al. (2009) cite several studies that have been conducted worldwide to estimate UHI intensity, presenting its maximum value and the approach followed for its estimation by each study. UHI has also been studied in some Mediterranean medium-sized cities. Kolokotsa et al. (2009) analyzed daily average values of air temperature recorded at Hania, Greece and found that UHI intensity ranged between 0.6°C and 8°C during the summer of 2007, its average value being 2.6°C. Sajani et al (2008) analyzed summer hourly temperature data to study the UHI that develops in Bologna, Italy and found

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that the nocturnal values of the UHI intensity were about 7°C. Montávez et al. (2000) analyzed hourly air temperature data and found that the UHI intensity in Granada, Spain was higher during winter, being always greater than 3°C and sometimes even greater than 7°C.

UHI significantly affects the thermal comfort conditions, the air pollution levels, and the energy consumption in urban areas. As it is characterized by increased temperatures, it induces adverse health effects related to thermal stress. Tan et al. (2010) found that heat-related mortality is higher in the city center than in the suburbs. As UHI also develops during the night, it deprives urban residents of the cool relief that is obtained by the inhabitants of the suburbs (Papanastasiou et al. 2010a). Additionally, Lai and Cheng (2009) studied the associations among UHI, air quality, and hospital respiratory admissions in Taichung, Taiwan and concluded that when the UHI intensity became equal or greater than 3°C the air quality significantly worsened due to accumulation of air pollutants. They stated that UHI generates convergence, transports air pollutants to urban settings, and consequently raises the risk of an increase in hospital respiratory admissions in the center of the UHI. Moreover, Rosenfeld et al. (1998) conclude that a ~3°C reduction in the intensity of the UHI in Los Angeles could result in 12% reduction of ozone exceedances. The UHI also has a direct effect on the amount of energy consumed for heating and cooling the buildings. The higher air temperatures that prevail in urban areas trigger a decrease in warming demand during the cold period of the year and an increase in cooling demand during the warm period. Santamouris et al. (2001) studied the impact of urban climate on the energy consumption of buildings in Athens, Greece. They found that the heating load of a building located in the city center could be reduced by up to 30% during the winter period. However, this status is totally reversed during the summer. According to the same study, the cooling load of urban buildings may be doubled, the peak electricity load for cooling purposes may be tripled especially for higher set point temperatures, while the minimum value of the coefficient of performance of air conditioners may be decreased by up to 25% because of the higher ambient temperatures.

Oke (1982) proposed the factors that contribute to the formation of UHI. These include the thermal properties of the construction materials, the anthropogenic heat production, the urban geometry and the evapotranspiration rate. A comparative assessment of these factors under calm, cloudless conditions at night was also performed by Oke et al. (1991). Additionally, the meteorological conditions play an important role in UHI development. Relative humidity, wind speed, precipitation, and cloudiness are considered to affect UHI intensity (Gedzelman et al. 2003; Kim and Baik 2002; Lee and Baik 2010). Gedzelman et al.

(2003) studied the UHI around New York and found among others that sea breeze (SB) can reduce and delay the UHI and displace its center. Kassomenos and Katsoulis (2006) examined the characteristics of the morning UHI in Athens, Greece and found that high UHI intensities are associated with anticyclonic conditions or advection in the lower troposphere. During summer, these conditions are also associated with the development of SBs which result to high air pollution levels over the city of Athens (Kambezidis et al. 1995). Arnfield (2003) provides a list of papers that were published during the period 1980–2001 and studied the relation of UHI intensity with meteorological conditions (wind speed, cloud cover, and anticyclonic conditions).

This paper aims to: (a) study the maximum UHI intensity levels in the urban area of Volos, Greece during winter and summer, (b) investigate the factors that affect them, and (c) develop models to predict the daily maximum hourly (DMH) UHI intensity.

2 Materials and methods

2.1 Study area

Volos is a medium-sized city located at the east coast of central Greece (Fig. 1a). It is inhabited by 118,564 people according to the 2001s national census. It is located at the north coast of Pagasitikos Gulf, which is an almost closed Gulf with an exit to the Aegean Sea. At a ~3-km distance to the northeast of the city center are the foothills of mountain Pelion, which extends from the north to the southeast of the city. Its higher peaks are at 1,551 and 1,471 m above mean sea level (amsl), which are to the northeast and to the east of the city, respectively, and at a distance of ~12 km from the city center. The western part of the greater urban area is surrounded by hills with height up to ~400 m. Roads inside the city are generally narrow and the street layout in the city center is based on a series of rectangular street grids, with their sides being parallel or perpendicular to the sea front. The traffic is occasionally fairly intense due to the city activities, the tourism, and the operation of the commercial and passenger port. There are two industrial areas to the west and a big cement industry to the east of the city.

2.2 Data sources

The data that were exploited in this study refer to a winter and a summer period (December 2009–February 2010 and summer 2010, respectively). No missing data were found for these two seasons.

Temperature data recorded by two meteorological stations were used to calculate the UHI intensity. The two stations are located in the city center (urban site, marked with U in

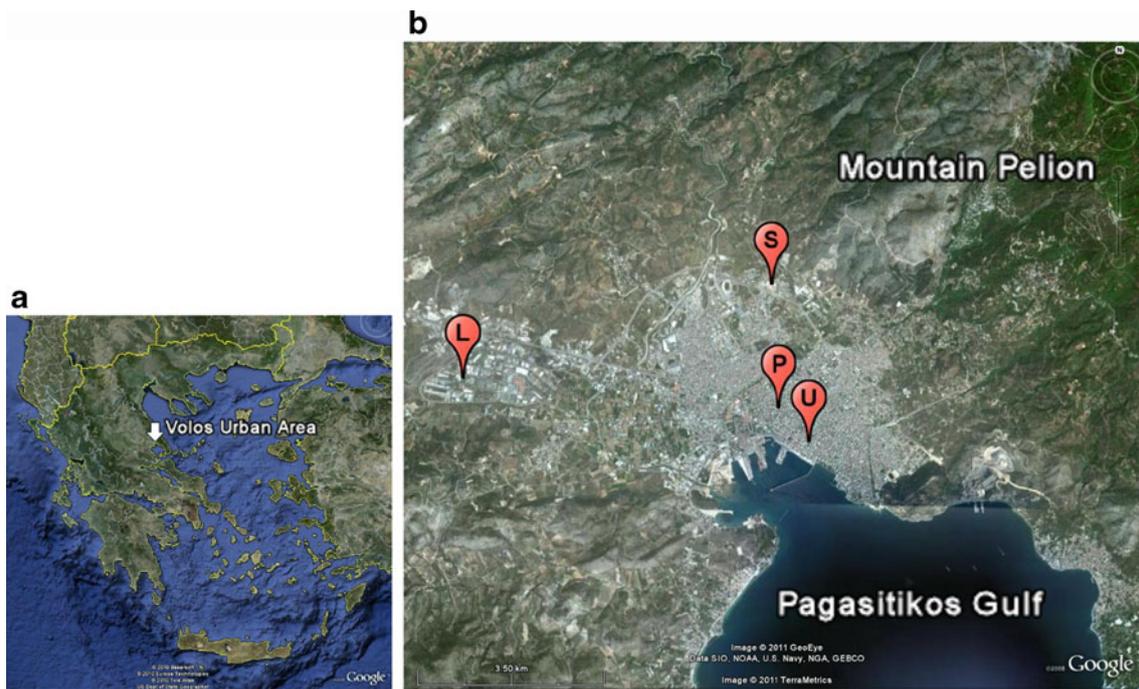


Fig. 1 Location of the city of Volos (*left*) and the monitoring sites within its greater area (*right*). Both maps are produced using Google Earth

Fig. 1b) and at a suburb (suburban site, marked with S in Fig. 1b) and they are part of the UHI monitoring network that was established in Volos in October 2009 by the Laboratory of Agricultural Engineering and Environment. Every station consists of a miniature device (type Onset Hobo Pro v2 U23-001), which is equipped with a data logger and two sensors that record temperature and relative humidity. Every device is placed in a white plastic shield with lateral slots in order to be protected from solar radiation and rain. The shields are fixed at the outer parts of balconies with south–southwest orientation. One of the network’s devices was calibrated by the Hellenic Institute of Metrology and was used to intercalibrate the rest prior to their installation. The distance between the urban and the suburban site is 3.1 km. The density and the height of buildings, as well as the traffic, are high at the urban site and low at the suburban one. The vegetation is low in both places. The height difference between the two sites is ~20 m. The measuring height (above ground level; agl) is 6.6 and 5.1 m at the urban and the suburban site, respectively. Temperature values were recorded in 15-min intervals; 1-h average values were calculated and used in this study.

The investigation of the factors that affect the maximum UHI intensity and the development of the regression models to predict the UHI intensity are based on pollution (i.e., PM10 concentration) and meteorological (i.e., relative humidity, precipitation, wind speed, wind direction, and solar radiation) data. PM10, relative humidity, wind speed, and wind direction were monitored by an automatic station

operated by the Department of Environment of the Prefecture of Magnesia. The station is a member of the national network of air pollution monitoring stations that was developed by the Hellenic Ministry for the Environment, Physical Planning and Public Works (current title since 2009: Hellenic Ministry for the Environment, Energy and Climate Change). It is located very close to the city center (latitude, 39°22’N; longitude, 22°57’E; altitude, 31 m amsl, marked with P in Fig. 1b) and its measurements are influenced strongly by traffic and city activities. The station provides data with 1-h temporal resolution. Precipitation and solar radiation were monitored by an automatic meteorological station operated by the Laboratory of Agricultural Engineering and Environment. The station is located to the west of the urban area (latitude, 39°22’N; longitude, 22°52’E; altitude, 62 m amsl, marked with L in Fig. 1b). The station provides data with 15-min temporal resolution; 1-h average values were calculated and used in this study.

One of the criteria that were applied to identify the SB days was the temperature difference between land and sea. Several new sea-surface temperature (SST) products from the Group for High Resolution Sea-Surface Temperature (GHRSSST) project (www.ghrsst.org) are available from the GHRSSST Global Data Assembly Center hosted at the Physical Oceanography DAAC (<http://poet.jpl.nasa.gov>). GHRSSST level 4 Operational Sea-Surface Temperature and Sea Ice Analysis (OSTIA) SST data (daily mean values) were used in this study. The OSTIA system uses satellite

data provided by the GHRSSST project, together with in situ observations to determine the sea-surface temperature (Martin et al. 2007; Stark et al. 2007).

2.3 Identification of sea breeze days

The following three criteria were applied in order to identify the SB days: (a) the wind blows onshore (in the range of 120° – 200°) for at least 2 h consecutively during the period of 2 h after sunrise until sunset, (b) the wind blows offshore (in the range of 270° – 50°) for the majority of hours from sunset to sunrise, and (c) the daily maximum air temperature over land is higher than the sea-surface temperature. Criteria (a) and (b) ensure the wind turning from offshore to onshore at the SB onset, while criterion (c) ensures that the physical mechanism that drives the SB development is active. Similar criteria have also been applied in other studies in the past (Furberg et al. 2002; Papanastasiou and Melas 2009).

3 Results and discussion

3.1 Characteristics of the maximum UHI intensity levels

The temperature data that were collected at the urban and the suburban sites during the winter and the summer were analyzed in order to calculate the DMH UHI intensity. Descriptive statistics and the frequency distribution of the DMH UHI intensity are presented in Table 1 and Fig. 2, respectively. Table 1 shows that the average maximum UHI intensity in Volos urban area is 2.0°C in winter and in summer, while the higher UHI intensities are observed in winter. Figure 2 supports these conclusions. It reveals that the DMH UHI intensity ranges between 1°C and 2°C with a frequency of occurrence in the range 46–48% during the winter and summer days, respectively, and between 2°C and 3°C with a frequency of occurrence in the range 44–50% during winter and summer days, respectively. Additionally, Fig. 2 shows that UHI intensity is higher than 3°C in very few cases that correspond to seven winter days and one summer day.

Figure 3 presents the time of the day when the maximum UHI intensity was observed. Sunrise and sunset during winter occur between 06:58–07:42 local time (LT) and 17:05–18:18 LT, respectively, while the mean solar noon time is at 12:31 LT. Sunrise and sunset during summer

occur between 06:02–06:54 LT and 19:56–20:52 LT, respectively, while the mean solar noon time is at 13:26 LT. LT in Greece is UTC+2 in winter and UTC+3 in summer. Figure 3 reveals that UHI is mainly a nocturnal phenomenon in Volos during both seasons. The maximum UHI intensity is more frequently observed in the nighttime than in the daytime also in many other cities worldwide, for example in Seoul (Kim and Baik 2002), in New York (Gedzelman et al. 2003), in Singapore (Chow and Roth 2006), in Hong Kong (Memon et al. 2009), in Granada (Montávez et al. 2000), and in Bologna (Sajani et al. 2008). It is worth mentioning that Kioutsioukis et al. (2010) analyzed temperature data recorded by 23 ground-based meteorological stations covering Greece and found that between 1955 and 2002, almost 74% of the stations showed a significant increase in the annual occurrence of warm nights. In winter in Volos, UHI starts developing after sunset and reaches its maximum intensity until 22:00 LT in half of the days examined. This fact could mainly be attributed to the nocturnal radiative cooling that is more rapid in the city surroundings. Urban areas cool at lower rates than its surroundings as air temperature decreases from late afternoon due to the different thermal behavior of the surfaces. The thermal behavior of a surface can be characterized by its thermal admittance. As materials used in urban areas, such as concrete, bricks, asphalt, etc. are characterized by high values of thermal admittance, they can capture, store, and release higher quantities of heat. Therefore, a large amount of incoming solar radiative energy can be absorbed by urban artificial surfaces during daytime, which can be compensated by nocturnal radiative cooling, consequently retarding the decrease of air temperature. In summer, UHI starts developing about 1 h after sunset and reaches its maximum intensity until 02:00 LT at 66% of the days examined. These maximum values could also be attributed to the nocturnal radiative cooling. However, Fig. 4 shows that these maximum values are observed somewhat later during SB days in summer. SB was developed in 75 days during summer 2010. SB advects cool sea air over the land, resulting in a reduction of air temperature during daytime. The cooling effect of SB diminishes gradually after the wind direction has changed, delaying the UHI formation.

Another factor that is related to UHI formation is the anthropogenic heat emissions. Sailor and Lu (2004) attribute anthropogenic heat emissions to vehicles, building sector, and human metabolism. The building sector plays an

Table 1 Descriptive statistics referring to DMH values

	Maximum value		Minimum value		Average value	
	Winter	Summer	Winter	Summer	Winter	Summer
UHI intensity ($^{\circ}\text{C}$)	3.4	3.1	0.8	1.0	2.0	2.0

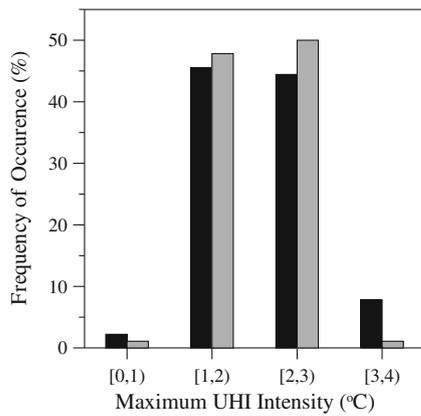
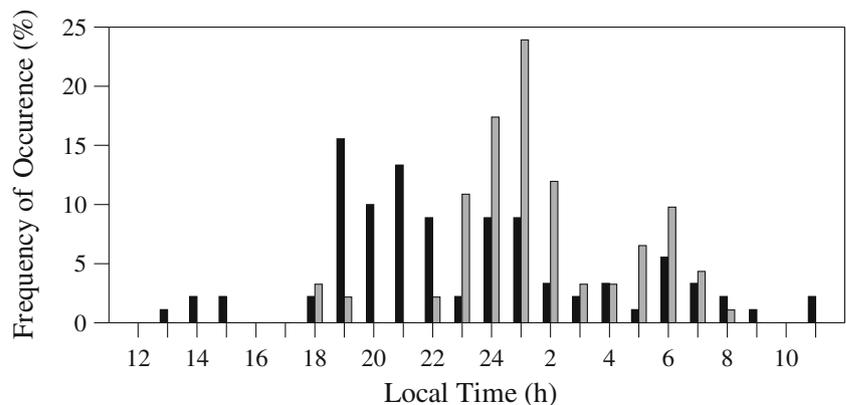


Fig. 2 Frequency of occurrence of the DMH UHI intensity during winter (black) and summer (gray) bars

important role in UHI development due to the operation of the central heating in winter and the air conditioners in summer. Memon et al. (2009) describes that pollutants could attenuate incoming solar radiation, a fact that triggers a reduction in air temperatures. On the contrary, traffic and central heating operation contributes to the release of anthropogenic heat, a fact that triggers an increase in air temperatures. So, the impact of traffic and central heating may be twofold and is attributed to the released quantities of smoke and other pollutants. Air conditioners contribute to the increase of UHI intensity as the heat dumped by air conditioning in summer causes a rise in air temperature. Wen and Lian (2009) found a rise of 2.56°C under inversion conditions and of 0.2°C under normal conditions in Wuhan, China. Uherek et al. (2010) discuss the impact of traffic and mobile air conditioners on climate change and on urban environment. Consequently, it is expected that traffic, central heating, and air conditioners influence the UHI intensity levels in Volos area. Anthropogenic activity has also been used to explain UHI peaks in other studies (Chow and Roth 2006; Giannaros et al. 2010; Jauregui 1997).

The UHI intensity may also be influenced by meteorological factors. This issue is discussed later in this paper.

Fig. 3 Time when the DMH UHI intensity is observed (black bars winter; gray bars summer)



However, at the moment the impact of wind speed is examined so as to indicate its contribution to the development of the nocturnal UHI. Figure 5 shows that wind speed during night time is lower than during day time in both seasons, revealing that the ventilation of the city center during the night hours is reduced. This condition supports the persistence of the thermal contrast between the urban area and its suburbs, favoring UHI development.

The analysis was extended to correlate the DMH UHI intensity with the values of meteorological (wind speed and relative humidity) and pollution (PM10 concentration) parameters at the time when it was observed. The corresponding correlation coefficients are presented in Table 2. The present analysis does not include the few days when the DMH UHI intensity was observed during daytime [i.e., between 09:00–17:00 LT in winter and 08:00–20:00 LT in summer].

The wind speed is negatively correlated with the DMH UHI intensity during both seasons (Table 2). A similar conclusion is also reported by other studies (Gedzelman et al. 2003; Kim and Baik 2002, 2005; Montávez et al. 2000). When the wind speed increases, advection of cooler air from the suburbs to the city center or advection of warmer air from the city center to the suburbs is enhanced, resulting in a reduction of the UHI intensity. Additionally, strong winds increase atmospheric mixing, lowering the temperature difference between the city center and the suburbs. Moreover, increased wind speed is often associated with increased amount of cloud cover that is also related to lower UHI intensities (Gedzelman et al. 2003; Kim and Baik 2002). Clouds block the incoming solar radiation during daytime, reducing city warming, as well the outgoing thermal radiation during night time, decreasing the radiative cooling rate in the suburbs.

Higher relative humidity values are related to lower UHI intensities during winter, as their correlation coefficient is negative (Table 2). Relative humidity in the atmosphere increases when water vapor pressure increases and saturation water vapor pressure decreases. These changes occur

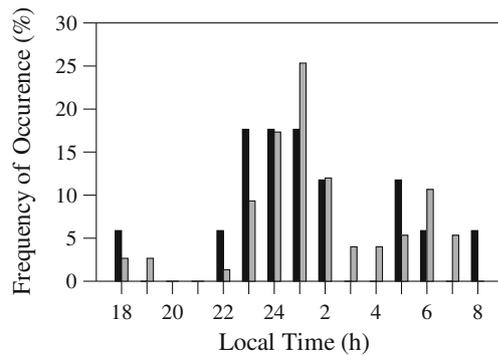


Fig. 4 As in Fig. 3, but in summer (*black bars* non-SB days; *gray bars* SB days)

when evaporation from the surface takes place. Evaporation triggers a decrease in near-surface air temperatures because of evaporative cooling, resulting in lower UHI intensities. Precipitation was observed during half of the winter days. This inverse correlation between relative humidity and UHI intensity is also reported in other similar studies (Kim and Baik 2002; Liu et al. 2007). However, DMH UHI intensities are positively correlated with relative humidity values during summer (Table 2). This rather confusing result could be attributed to the prevailing meteorological conditions. Relative humidity in Volos area is lower during summer than during winter. The median of the DMH values, the daily minimum hourly values and the daily average values of relative humidity during winter were equal to 91%, 53%, and 71%, respectively, while the corresponding summer values were 64%, 40%, and 52%. Evaporation is much less intense during summer as precipitation was observed only during 9 days. The major factor that drives the summer relative humidity levels is the SB circulation that frequently develops in the area and carries humid air masses from the sea (Papanastasiou and Melas 2009). SB circulation is favored when anticyclonic conditions prevail, which are also associated with higher UHI intensities as it is mentioned later in this paper. Consequently, this weather type is simultaneously related to higher UHI intensities and to higher humidity levels. This rationale could explain the positive correlation coefficient

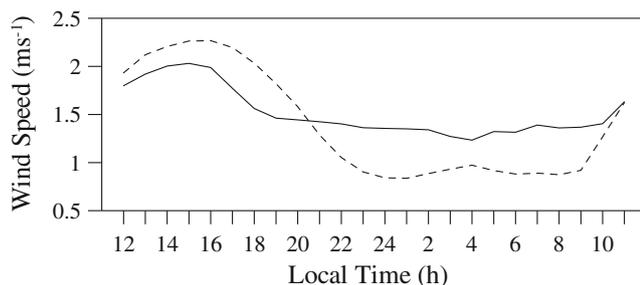


Fig. 5 Diurnal variation of wind speed (*solid line* winter; *dashed line* summer)

Table 2 Correlation coefficients between DMH UHI intensity and wind speed, relative humidity and PM10 concentration

Seasonal DMH UHI intensity	Parameter		
	WS	RH	PM10
Winter	-0.29	-0.31	0.22
Summer	-0.22	0.17	-0.14

between the DMH UHI intensity and the relative humidity values during summer SB days. During summer nonSB days, the humidity levels are lower than during SB days as wind blows offshore, while wind speed is generally higher than during SB days (Papanastasiou and Melas 2009). Consequently, lower relative humidity values are associated with higher wind speeds that are related to lower UHI intensities, a condition that also supports the positive correlation coefficient found between relative humidity and DMH UHI intensity in summer.

The impact of pollution levels (i.e., PM10) on maximum UHI intensity is found to be different during winter and summer. As it was already mentioned, pollutants could trigger either an increase or a decrease in air temperatures. An increase in PM10 levels is associated with an increase in maximum UHI intensity during winter, as their correlation coefficient is positive (Table 2). Papanastasiou and Melas (2010) found that the PM10 concentration in Volos tends to be higher in winter and lower in summer, attributing this seasonal variability to the operation of central heating and to the seasonal variation of the atmospheric boundary layer height which is generally lower during winter and becomes higher during the warm period of the year. As central heating is a major source of anthropogenic heat, it contributes to the increase of urban temperatures mainly during the night, when lower air temperatures are observed, supporting the UHI development. Additionally, the PM10 emission rate due to the central heating operation is usually higher during the night. Therefore, it could be considered that PM10 attenuates the outgoing thermal radiation during night time stronger than the incoming solar radiation during daytime, a fact that retards the nocturnal radiative cooling of the urban area. On the contrary, the correlation coefficient between PM10 concentration and DMH UHI intensity becomes negative during summer (Table 2). This fact reveals that PM10 affects the net energy balance by attenuating the incoming solar radiation, triggering a reduction in air temperatures and consequently a reduction in heat that is captured and stored by materials in the urban area. Therefore, as lower quantities of heat are released into the atmosphere, so UHI intensity is decreased. It is worth mentioning that dust transport events frequently occur in Greece during summer (Papanastasiou et al. 2010b; Papayannis et al. 2005). Such

events trigger an increase in PM10 levels (Kaskaoutis et al. 2008; Katragkou et al. 2009); therefore, the attenuation of the incoming solar radiation becomes stronger when they occur.

3.2 Estimation of the maximum UHI intensity

The fact that UHI is related to thermal comfort conditions, air pollution levels and energy consumption in urban areas, provides a motive to develop tools to predict its intensity. Such tools could be useful to environmental, medical, and energy managers when establishing their short- and long-term strategies. Additionally, they could be applied by building designers when calculating the energy demands of a building (Kolokotroni et al. 2009).

The quantitative estimation of the DMH UHI intensity is based on two analytical expressions (Eqs. 1 and 2) derived by multiple linear regression analysis (MLRA). The first model (Eq. 1) may be applied to predict the DMH UHI intensity during winter, while the second one (Eq. 2) in the summer. As before, the few days when the DMH UHI intensity was observed during daytime were not included in the MLRA. The expressions of the two regression models have the following form:

$$y_1 = m_1 \cdot x_1 + m_2 \cdot x_2 + m_3 \cdot x_3 + m_4 \cdot x_4 + m_5 \cdot x_5 \quad (1)$$

$$y_2 = m_6 \cdot x_1 + m_7 \cdot x_2 + m_8 \cdot x_6 + m_9 \cdot x_7 + m_{10} \cdot x_8 \quad (2)$$

where:

- y_1, y_2 The natural logarithm of the DMH UHI intensity (°C) during winter and summer, respectively
- x_1 An index used to describe the weekly variation of the maximum UHI intensity
- x_2 The minimum hourly value of relative humidity (%) during daytime
- x_3 The natural logarithm of the previous day's maximum hourly UHI intensity (°C)
- x_4 The previous day's maximum hourly value of solar radiation (Wm^{-2})
- x_5 The daily minimum hourly value of wind speed (ms^{-1})
- x_6 The previous day's maximum hourly UHI intensity (°C)
- x_7 The daily average value of wind speed (ms^{-1})
- x_8 The natural logarithm of the daily average of PM10 concentration (μgm^{-3})

The selection of the predictors that were included in the models was based on two criteria: every independent variable has to correlate adequately with the DMH UHI intensity, while its inclusion in the model has to improve the quality of the prediction. The models incorporate wind speed, relative humidity, and PM10 concentration, whose

impact on UHI intensity was previously discussed but also some other parameters that are considered to affect UHI intensity, whose impact is presented below.

Sun is the primary source of heating in an area. Solar radiation is stronger and more persistent during summer than during winter as cloudiness is usually absent or very light in the daytime during summer. Therefore, the day-to-day variability in the amount of the incoming solar radiation is small during summer. Due to this reason, the correlation coefficient between the DMH value of solar radiation and the DMH UHI intensity remains lower than 0.10 in summer. On the contrary, their correlation coefficient becomes higher than 0.40 during winter. On this account, solar radiation was used as a predictor only in the winter model.

Earlier studies have shown that current UHI intensity levels are dependent on the previous day's UHI intensity levels. Kim and Baik (2002) found a positive relation between them when studying the maximum UHI intensity levels in Seoul and attributed this fact to the duration of certain weather types. Kassomenos and Katsoulis (2006) found that high UHI intensities in Athens, Greece are associated with anticyclonic conditions or advection in the lower troposphere, while low UHI intensities are associated with strong northeasterly winds. Pinho and Manso Orgaz (2000) also state that weak and high UHI intensities are associated with low- and high-pressure situations, respectively. For this purpose, the previous day's UHI intensity was included in both models. The DMH UHI intensity is positively correlated to the maximum hourly UHI intensity of the day before during both seasons. The correlation coefficients equal to 0.25 and 0.23 for winter and summer days, respectively.

Averages of the weekly variation of DMH UHI intensity are presented in Fig. 6. This figure shows that maximum

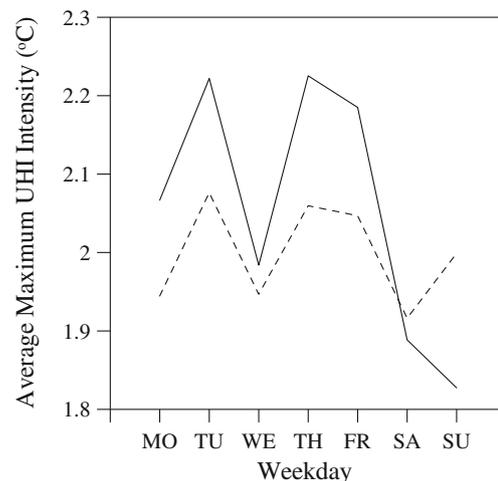


Fig. 6 Weekly variation of the DMH UHI intensity (solid line winter; dashed line summer)

UHI intensity exhibits a weekly variation that is more pronounced during winter. The weekly range of DMH UHI intensity is not very large, being 0.4°C and 0.2°C during winter and summer, respectively. The weekly variance of UHI intensity may be attributed to the variability of the city activities, such as traffic, opening hours of the shops etc, which induces a short-term variation of anthropogenic heat emissions. The lower UHI intensities are observed on Mondays, Wednesdays, and Saturdays, when shops are closed in the afternoon, while higher UHI intensities are observed on Tuesdays, Thursdays, and Fridays, when shops are opened in the afternoon. The UHI intensity is lower during weekends than during weekdays in winter, as traffic and commercial activities are significantly reduced. However, UHI intensity levels during weekends in summer are not significantly reduced compared to corresponding weekdays levels, as Volos is a popular summer destination for domestic tourists. The weekly variation of UHI intensity is also examined in other studies. Figuerola and Mazzeo (1998) reported that during the cold period, a maximum heat island of 3.0°C was observed in the early morning during midweek days in Buenos Aires while on weekends this value dropped to ~2°C. They also stated that UHI's weekly variation was not significant in the warm months. Additionally, Kim and Baik (2005) detected that the UHI in Seoul is stronger during weekdays than on weekends and reported a maximum temperature difference of 0.6°C. Both studies attributed the UHI's weekly variation to variations in anthropogenic heat emissions. In this study, an index was introduced as a predictor in both models in order to parameterize the short-term variability of anthropogenic heat emissions. The index was developed by normalizing the average UHI intensities for each day of the week by the average UHI intensity for Sundays. National holidays are treated as Sundays. The correlation coefficient between this index and the DMH UHI intensity equals to 0.27 and 0.17 for winter and summer days, respectively.

The data were split in two sets. Of the data, 66% was used to develop the two models (development set) and the rest 34% of the data was used to validate the models (validation set). The quality of the developed models was examined via two statistical estimators, namely the mean absolute error (MAE) and the index of agreement (IA) (Joliffe 2003; Wilks 1995). They are defined by Eqs. 3 and 4, where \bar{O} , O_i , P_i , and N are the mean of observed values, the observed values themselves, the predicted values and the number of data points, respectively. MAE is a measure of the total deviation of the predicted values from the observed values and illustrates the presence of significant mispredictions, while IA indicates the degree to which the predictions of the model are error free. Both estimators are

considered as good overall measures of model performance and have been widely used in environmental studies.

$$\text{MAE} = \frac{\sum_{i=1}^N |O_i - P_i|}{N} \quad (3)$$

$$\text{IA} = 1 - \frac{\sum_{i=1}^N (O_i - P_i)^2}{\sum_{i=1}^N (|P_i - \bar{O}| + |O_i - \bar{O}|)^2} \quad (4)$$

The MAE of the winter and the summer model was found to be 22.8% and 20.3% of the mean of the observed values, respectively, while the corresponding values of the IA 0.71 and 0.52. These results indicate that the two models can adequately predict the maximum UHI intensity. The models can be improved in the future so as to achieve better results, as they have interesting practical applications. As this study is based on 1-year data, it is expected that the accuracy of prediction will increase when more data be incorporated in MLRA. Additionally, the inclusion of other predictors in the future, most of which unfortunately are unavailable at the present, may improve the forecasting ability of the models. These are related to anthropogenic heat releases and meteorology. The influence of anthropogenic heat on UHI might be better accounted for if quantitative data about energy consumption and vehicular traffic are taken into account. Regarding the impact of meteorology on UHI intensity, further research is needed to investigate the relation between UHI intensity and weather types. Moreover, the inclusion of cloudiness and other parameters related to clouds, like cloud base, and of parameters related to temperature inversions, like magnitude and height, might improve the prediction. Gedzelman et al. (2003) report that the UHI intensity increases as the height of the cloud base and the magnitude of the surface-based temperature inversion observed at 12:00 UTC increases.

4 Summary and conclusions

This paper studied the maximum UHI intensity levels during winter and summer in Volos, Greece and confirmed that UHI develops also in medium-sized cities. The average maximum UHI intensity is 2.0°C during both seasons, while the higher UHI intensities are observed in winter. The maximum UHI intensity occurs at night time in the vast majority of the examined days during both seasons. In

winter, UHI starts developing after sunset and reaches its maximum intensity until 22:00 LT in 50% of the days, while in summer it starts developing about 1 h after sunset and reaches its maximum intensity until 02:00 LT in 66% of the days.

UHI can be attributed to the following factors:

1. The nocturnal radiative cooling is more rapid in the city suburbs due to the different thermal behavior of the surfaces. This different cooling rate between the urban areas and their suburbs results in the growth of a temperature difference until a maximum is reached some hours after sunset.
2. The anthropogenic heat emitted by vehicles and the building sector (mainly due to the operation of the central heating in winter and of air conditioners in summer). This study revealed the impact of atmospheric pollution on UHI intensity. Pollutants can attenuate the incoming solar radiation triggering a reduction in urban air temperatures but they can also attenuate the outgoing thermal radiation during night causing a delay in the radiative cooling of the urban area. The first mechanism was found to be stronger in summer, while the latter was found to be more pronounced in winter. Additionally, this study showed that the maximum UHI intensity exhibits a weekly cycle that could be attributed to the weekly cycle of the city activities.
3. Meteorological factors. The DMH UHI intensity is (1) positively correlated with solar radiation and relative humidity during summer and (2) negatively correlated with wind speed and relative humidity during winter. Additionally, it is positively correlated with the previous day's maximum hourly UHI intensity, a fact that brings out the impact of certain weather types on UHI intensity. The impact of SB development on UHI was also examined and it was found that SB retards the UHI formation in summer.

MLRA was performed to develop two models, one for winter and one for summer, which could be applied to estimate the DMH UHI intensity. Parameters related to meteorology (i.e., wind speed, relative humidity, solar radiation, and previous day's maximum hourly UHI intensity) and to anthropogenic heat emissions (i.e., PM10 concentration, weekly cycle of city activities) were used by the models as independent variables. The statistical estimators used to evaluate the models' performance (i.e., MAE and IA) revealed that the agreement between the predicted and the observed values is generally good. However, the models could be improved in the future as they have interesting practical applications related to human welfare and energy management.

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