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Urban heat island in southern Europe: The case study of Hania, Crete

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Abstract

The aim of the present paper is to analyze the results of the urban heat island research for a coastal densely built small Mediterranean town namely Hania, Crete, Greece. The specific research targets to verify the existence, the intensity, the size and the form of the urban heat island phenomenon in the specific region as well as to understand its correlation with the local weather conditions. Nine urban and three rural meteorological stations are used for this study. Temperature and relative humidity measurements are collected from May 26, 2007 until October 24, 2007. In parallel, meteorological data including wind speed and direction, barometric pressure, sunlight and precipitation for the specific region are collected and elaborated for cross-correlation with the appearance of the urban heat island (UHI) phenomenon. During summer period, where the temperature is high, the UHI takes its maximum intensity, of about 8 °C. Also, the form of the UHI is strongly influenced from the wind speed and direction. The northern winds expand the UHI front, while the western winds contribute to the UHI reduction. Finally the Discomfort Index (DI) is calculated for the 2007 summer period to indicate the outdoor living conditions.

Keywords: Urban heat island; Urban discomfort; Heat stress; Coastal area

1. Introduction

Urban settlements are the most important human habitat. Approximately 50–60% of the world population lives in cities and towns. The second half of the last century was a period of the more intensive urbanisation that earth has never experienced. In fact, urban population has increased from 160 millions to about 3 billions in just 100 years, and it is expected to increase to about 5 billion by 2025. The quality of urban agglomerations is mainly defined by the type and the strength of the anthropogenic activities, the existing infrastructures and the used resources, the generated wastes and emissions and the corresponding environmental impact (Hardy et al., 2001).

Cities are often warmer than their unbuilt surroundings (Landsberg, 1981; Oke, 1982). This phenomenon which is governed by significant differences between the energy budgets of cities and the countryside is called the urban heat island phenomenon (Crutzen, 2004). Significant research efforts have been performed to evaluate the urban heat island phenomenon's impact on the urban environment (Akbari et al., 1999; Mihalakakou et al., 2000; Santamouris, 2001; Santamouris et al., 2007a; Alcoforado and Andrade, 2006; Kolokotroni et al., 2006; Kolokotroni and Giridharan, 2008). The heat island studies on European level during the last 15 years are summarised by Santamouris, 2007. Based on this study, the quantification of urban heat island phenomenon in Europe is analysed using the following tools:

Statistics of temperature differences between pairs or groups of urban and rural stations.
Results obtained by networks of fixed stations in a city.
Mobile stations across urban areas.

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The increased urban temperatures created by the UHI are extensively studied (Livada et al., 2002; Mihalakakou et al., 2004; Livada et al., 2007). The impact of the wind, cloud cover and generally of cyclonic or anticyclonic conditions on UHI intensity is also reported (Papanikolaou et al., 2008; Stathopoulou et al., 2008, 2009). In addition, the diurnal and seasonal variations are discussed by many researchers (Santamouris et al., 2007a; Alcoforado and Andrade, 2006; Kolokotroni et al., 2006; Kolokotroni and Giridharan, 2008).

The urban heat island's impact on the cooling load of buildings, the peak electricity demand for cooling and the efficiency of air conditioners and passive cooling techniques is of a major importance (Cartalis et al., 2001; Santamouris et al., 2007b; Santamouris et al., 2001; Hassid et al., 2000; Geros et al., 2005).

Additionally, the urban heat island phenomenon in coastal cities is analysed by various researchers. Pinho and Manso Orgaz, 2000 studied the heat island phenomenon in the coastal city of Aveiro, Portugal. It was found that the heat island intensity is almost 7.5 °C. Moreover Saaron et al., 2000 measured the urban heat island in Tel-Aviv. Air temperature differences of up to 6 °C at the street level and of 2 °C at the roof level were identified between the city centre and the south-eastern margins of Tel-Aviv.

Based on the above analysis, it is expected that urban heat island phenomenon occurs in highly populated urban areas. Moreover the majority of the urban heat island studies are performed in areas with population higher than 120.000–150.000 inhabitants (Santamouris, 2007). The aim of the present work is to analyse the existence, the intensity and the form of the urban heat island phenomenon in a coastal densely built small Mediterranean town namely Hania, Crete, Greece.

The present paper is structured in three more sections. Section 2 provides the description of the region and the prevailing climatic conditions. Section 3 analyses the experimental procedure while Section 4 includes the experimental results and discussion. Finally, Section 5 summarises the conclusions and discusses issues for future consideration, research and development.

2. Description of the area and prevailing climatic conditions

Hania is a north oriented coastal town whose northern border is defined by the Aegean Sea. The city of Hania is inhabited by 53,000 residents and is located in a plain, at the base of a large circular shaped peninsula named Akrotiri. The southern part of the plain is constricted by the White Mountains with more than 2000 m altitude (see Fig. 1). The most interesting characteristic of the specific region is the fact that Hania is the third most densely populated area in Greece following Athens and Thessaloniki metropolitan regions having 4444.1 inhabitants/km^2.

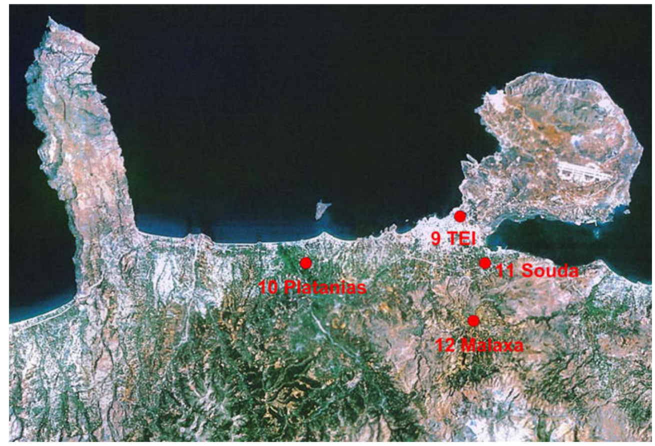

Fig. 1. The three rural measurements' locations.

The synoptic conditions occurring over southern Greece and consequently over Hania, Crete during summer is classified by Kassomenos, 2003 into four categories or clusters:

- Cluster 1: The synoptic conditions are characterised by low solar radiation and temperature and high humidity levels. This synoptic situation favours the establishment of local circulations as a sea breeze.
- Cluster 2 is frequent during July and August. Days characterised as cluster 2 present the highest solar radiation and air temperatures, while the humidity levels are low.
- Cluster 3 is typical of summertime. It presents its highest frequency during July and August. During the days classified in this cluster, the pressure gradient over Greece is very weak and the humidity is high. This situation favours the formation of local circulation systems i.e., sea breezes.
- Cluster 4 is similar to cluster 2. The main difference between them is the higher pressure and the weaker pressure gradient over the Aegean Sea in cluster 4, leading to a significant weaker NE flow over the Aegean Sea.

The prevailing anticyclonic conditions contribute to the development of the heat island during summer. On the other hand the predominant high pressure systems combined with low pressure ones over the Aegean Sea result to increased wind regimes that may decrease the persistence of the UHI subject to suitable cities' orientation and form.

3. Experimental procedure

The experimental procedure includes the following steps:

1. Formulation of a measurements' grid including urban and rural stations.
2. Collection of measurements for a whole summer period.
3. Collection of weather data.
4. Initial elaboration of data.
5. Analysis of experimental results.

3.1. The measurements' grid

In the present study, a measurements' grid is set up consisting of nine urban and three rural stations. The measurements' grid includes:

- Eight data loggers (Supco – model LOGiTpc) measuring dry bulb temperature and relative humidity. The measurements accuracy is ±0.5°C and ±1% for temperature and relative humidity, respectively. The eight data loggers are positioned on the second floor of specific city dwellings (around 3.5–4 m above ground). All devices are placed in meteorological cages for weather and radiation protection.
- Four fully equipped meteorological masts measuring dry bulb temperature, relative humidity, wind speed and wind directions located at the city's surroundings (see Fig. 1). One of the four meteorological masts (TEI: no 9) is also equipped with atmospheric pressure and global solar radiation sensors and is considered the reference station.

The measuring devices are spread to cover the urban area under study. The sensors' positioning is realised based on the following criteria:

- Coverage of the city centre as representatively as possible (stations 2–5).
- Coverage of the most densely built neighbourhoods (stations 1, 7 and 8) around the city centre.
- Coverage of the coastal line (stations 5, 8 and 9).

The urban stations are stations 1–8 (see Fig. 2), the suburban station is station no 9 (reference station) while the rural stations are stations 10, 11 and 12 (Figs. 1 and 2). A short description of each location is tabulated in Table 1.

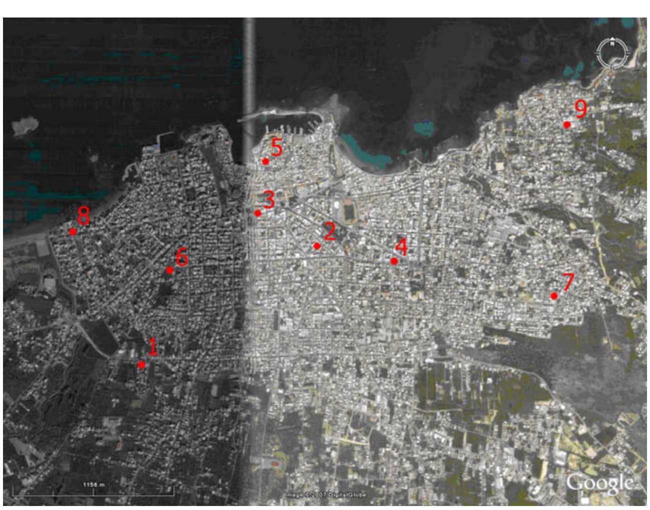

Fig. 2. The nine urban measurements' locations.

3.2. Measurements period

The measurements were performed during summer 2007 and more precisely from May 2007 until October 2007. The measurements' time interval is 10 min and then the measurements are elaborated to be presented on daily or hourly basis.

3.3. Initial data analysis

As it is previously mentioned, data analysis aims to investigate UHI intensity and its impact on the outdoor comfort conditions. An initial elaboration is performed for the temperature and relative humidity measurements illustrated in Figs. 3 and 4, respectively. The highest and lowest temperature values among all urban locations are recorded in station no 3 (city centre) and station no 9 (reference station), respectively. The initial temperature measurements analysis indicates that there is a significant temperature increase in the city centre (station no 3: Plateia 1866) comparing to the suburban area (station no 9: TEI/Reference). On the other hand the relative humidity in the city centre (station no 3) is the lowest among all stations, indicating that the penetration of the relative humidity in the main city is limited. The relative humidity takes its maximum values at the coastal line stations (i.e., stations 5, 8 and 9) as expected.

3.4. Outdoor comfort conditions

Various indices are proposed by the international literature for the evaluation of the outdoor comfort conditions.

The wet bulb globe temperature (WBGT) is defined by (Buonanno et al., 2001):

$$\mathrm{WBGT} = 0.7T_w + 0.2T_G + 0.1T_a \tag{1}$$

Where:

T_w, wet bulb temperature (°C)
T_G, globe temperature (°C)
T_α, dry bulb temperature (°C)

Generally when WBGT is lower than 26.6 °C there are no discomfort problems while if WBGT is higher than 32 °C the heat stress is on hazardous levels for the population.

Moreover, the cooling power (CP) index was introduced by Cena et al., 1966 to evaluate the outdoor conditions, defined as:

$$\mathrm{CP} = (0.421 + 0.087u)(36.5 - T_a) \tag{2}$$

where
u is the wind velocity in m/s
T_α, dry bulb temperature (°C)

Finally Discomfort Index (DI) is one of the most significant indices that may be correlated to the UHI perfor-

Table 1
Locations' characteristics.

No	Name	Characteristics of selected locations
1	Gogoni street	Urban region boundaries, densely populated neighbourhood
2	Sfakion street	Dense urban area, high rise buildings
3	Square 1866	Dense urban areas, high rise buildings
4	Dikastiria square	Dense urban area, large streets
5	Old town	Low rise buildings, small houses and narrow streets
6	Botsari street	Mediate urban density, large streets
7	Lentariana	Mediate urban density, urban boundaries
8	Nea Chora	Dense urban coastal area
9	TEI	Suburban area: increased vegetation and low rise buildings. Reference station
10	Platanias	West side of the city (coastal valleys -23 m altitude). Rural station
11	Souda	East side of the city (small hills-118 m altitude). Rural station
12	Malaxa	South side of the city (556 m altitude). Rural station

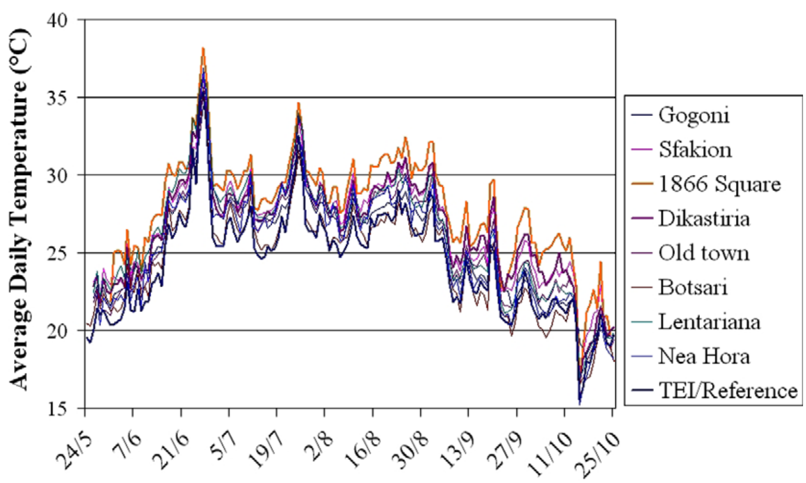

Fig. 3. Average daily air temperature measurements in all locations.

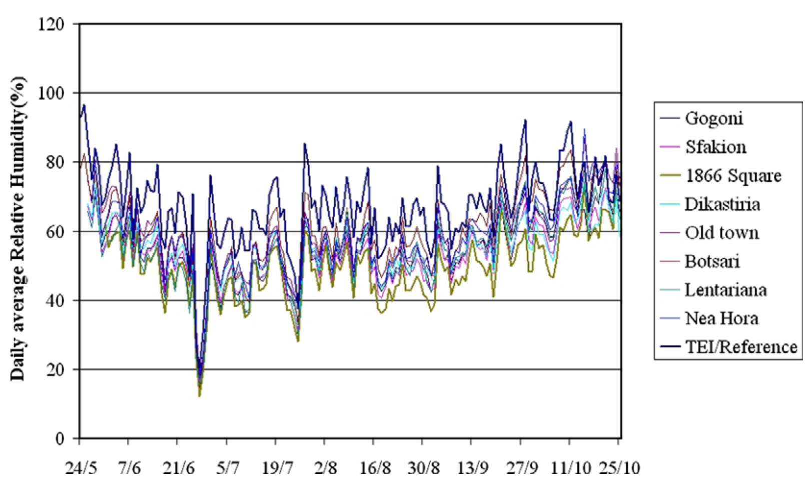

Fig. 4. Average daily relative humidity measurements in all locations.

mance. DI is calculated using Eq. (3) or Eq. (4) (Tselepidaki et al., 1992):

$$DI = T_a - 0.55(1 - 0.01 \cdot RH)(T_a - 14.5) \quad (3)$$

Where DI, is the Discomfort Index (°C)
RH, is the relative humidity (%)

$$DI = 0.4(T_a + T_w) + 4.8 \quad (4)$$

For comparison purposes, the various discomfort indices are calculated using the meteorological data of station no 9 (reference station) for all days and are depicted in

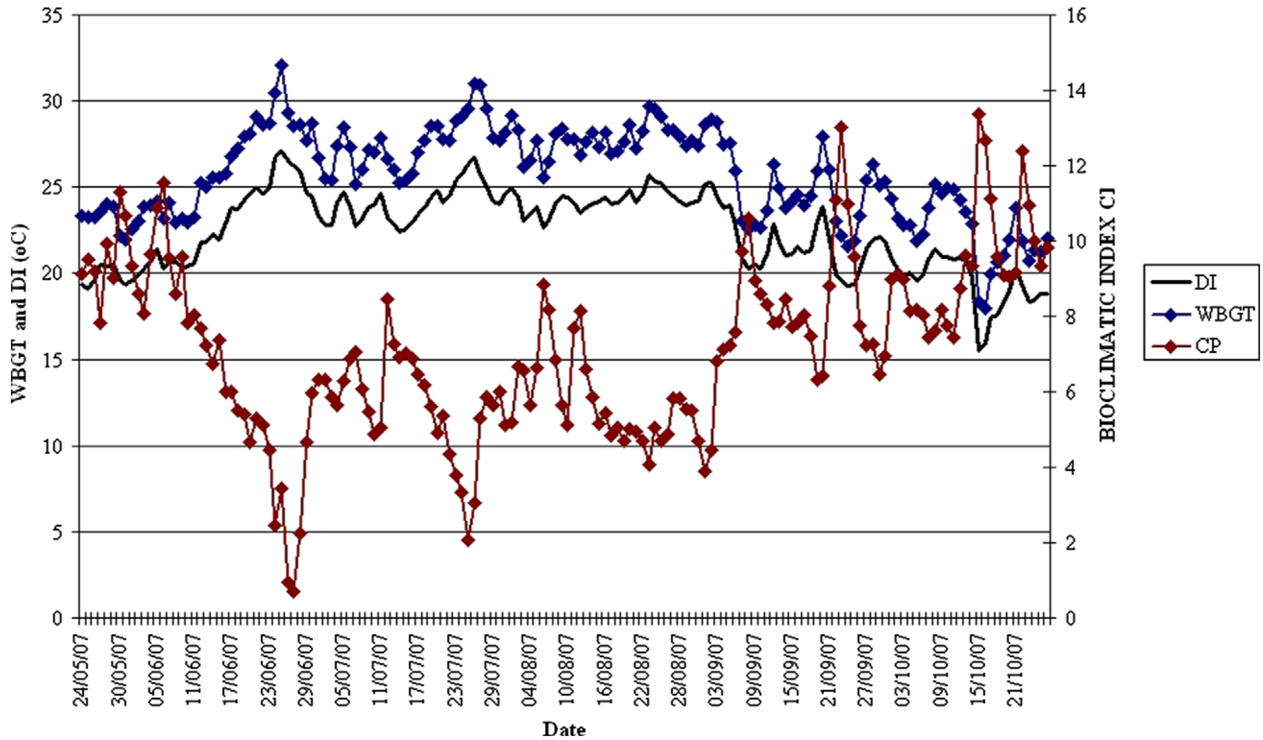

Fig. 5. The various outdoor comfort indices for the reference station (station no 9).

Fig. 5. All three indices characterise similarly the outdoor conditions. For example on 21/6/2007 the values of the three indices for the reference station are:

$$DI = 24.9\,^{\circ}C, CP = 5.28, WBGT = 29\,^{\circ}C$$

corresponding to warm outdoor climatic environment.

For the analysis of UHI in Hania the DI is utilised as on the one hand, it can be calculated by the temperature and relative humidity only and on the other hand it provides an accurate indication of the external conditions.

Fig. 6 illustrates the calculated DI for the relevant locations. DI takes its highest values in the urban stations (i.e., stations nos 2–4) while it is decreased in the reference station (station no 9) following closely the UHI intensity. A detailed analysis of UHI layouts and isotherms are included using the city plan (Google Earth©), while isothermal lines are added by Surfer 8 software (Golden Software©).

4. Experimental results and discussion

In the framework of the experimental results' analysis several city thermal profiles are created in order to analyse the UHI intensity during summer period in Hania. Moreover, heat waves are extensively examined. Finally the correlation between the heat island's appearance and the local climatic conditions is investigated.

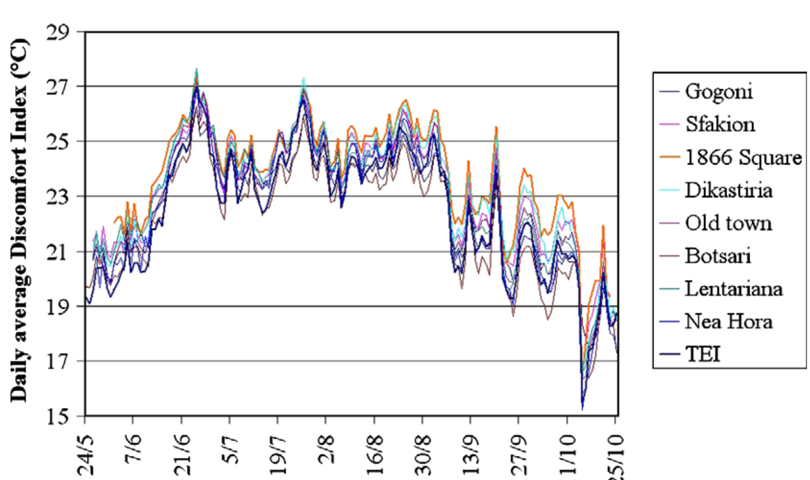

Fig. 6. Average DI calculations for all locations.

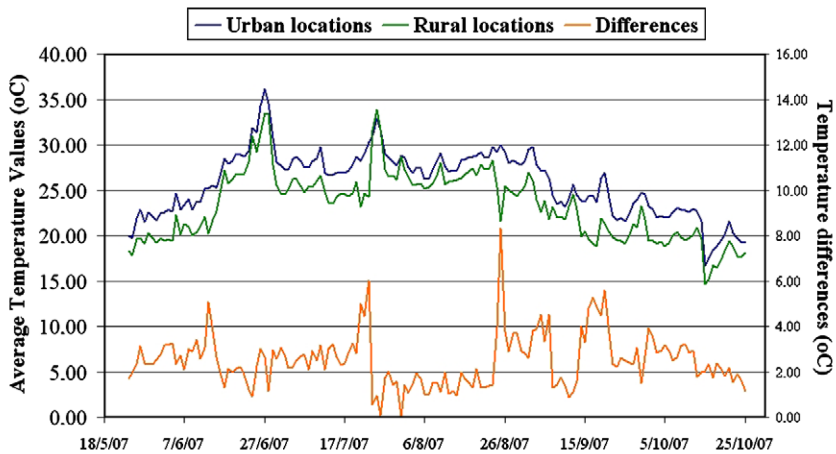

Fig. 7. The average daily temperatures of all urban and rural locations.

4.1. Daily and monthly variations

The daily average temperatures of urban and rural locations are illustrated in Fig. 7. The difference between the urban and rural stations' temperatures is fluctuating for the overall period having a maximum of 8 °C on 25/8/2007 and a minimum of 0.6 °C on 31/7/2007. The average difference for the whole measurements period is almost 2.6 °C.

On a monthly basis the average temperatures of the urban and rural locations are illustrated in Fig. 8. The UHI intensity increases after June and decreases after September. More precisely, the temperature's difference between urban and rural areas is less than 1 °C in June, approximately 3 °C within July, August and September, and 2 °C in October. Additionally the increase rate during the early summer is more intense than the decrease rate of temperatures during autumn.

The monthly temperature differences between the city centre stations (stations nos 2–4) and the rest urban stations are depicted in Fig. 9. The temperatures' differences are almost 1 °C in June and July, almost 1.8 °C in August, 2 °C in September and is reduced in October. The highest difference occurs during September.

4.2. Diurnal variations

The UHI intensity over Hania region is mapped using Google Earth for all measurements days. Indicatively the isothermal images of the UHI intensity over Hania for various days are illustrated in Figs. 10–12, respectively. Daytime is considered between 7:00 and 19:00 and nighttime

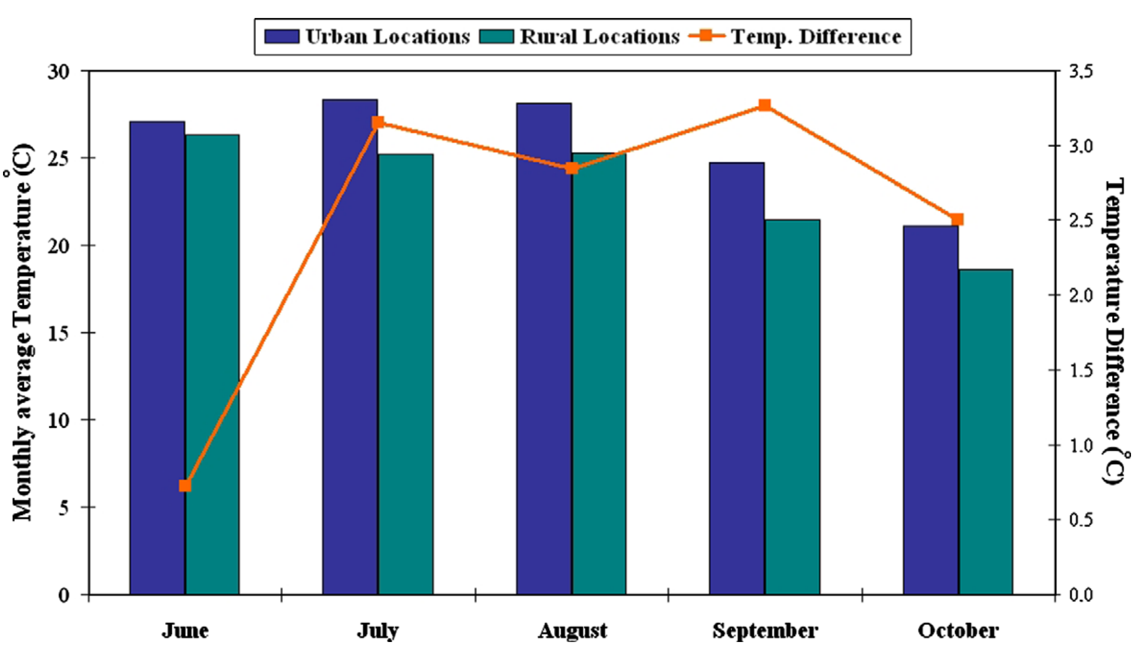

Fig. 8. Monthly average temperatures of urban and rural locations.

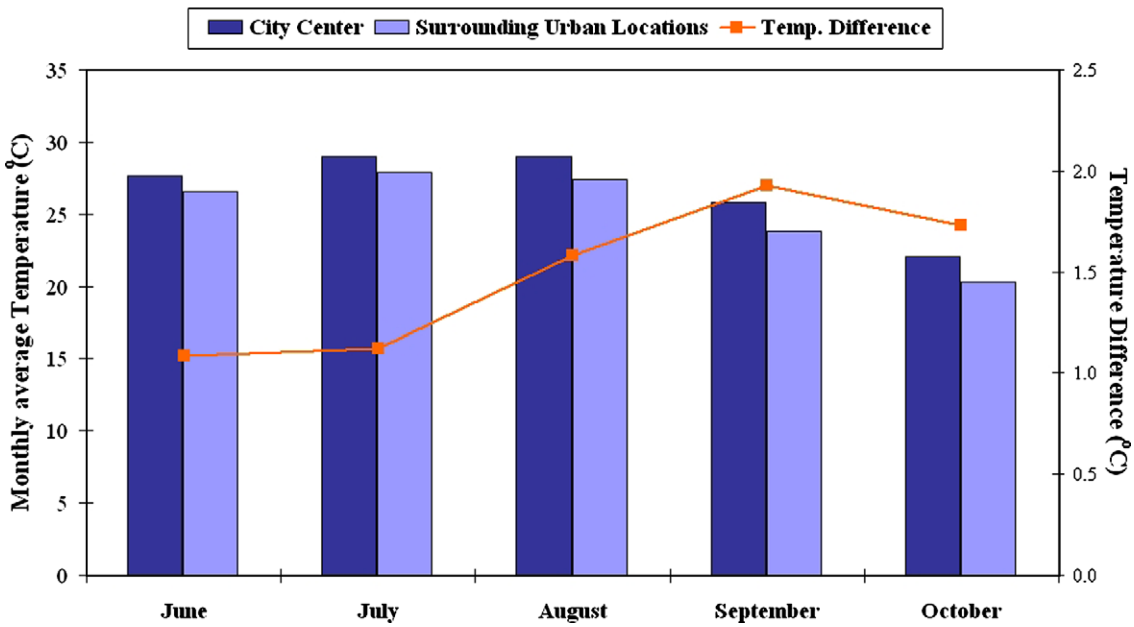

Fig. 9. Monthly average temperatures of the city centre and other urban locations.

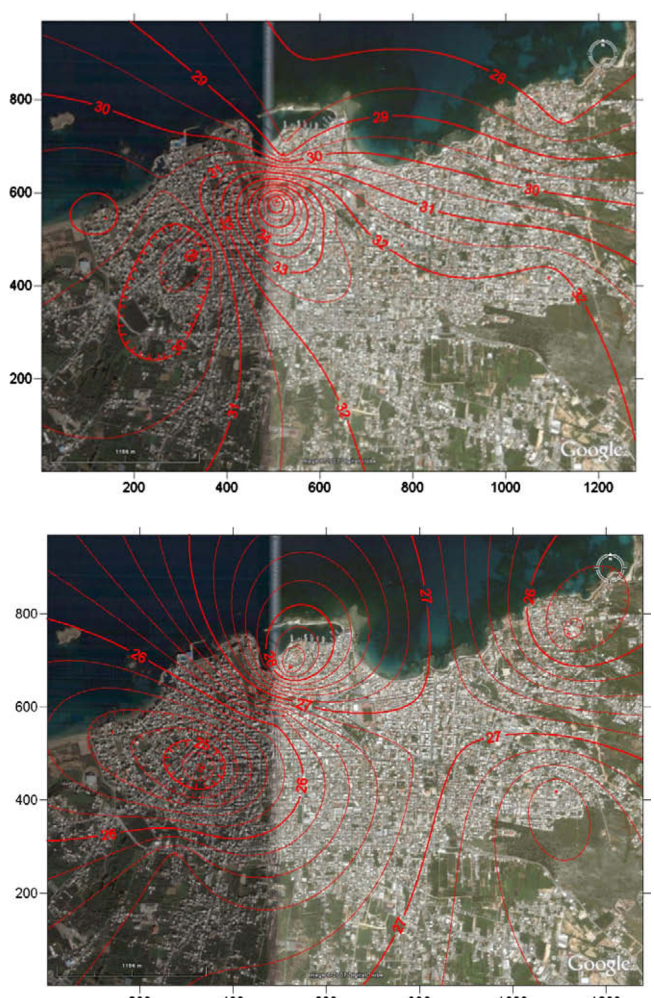

Fig. 10. The UHI in Hania during daytime (upper graph) and nighttime (lower graph) on 22/6/2007.

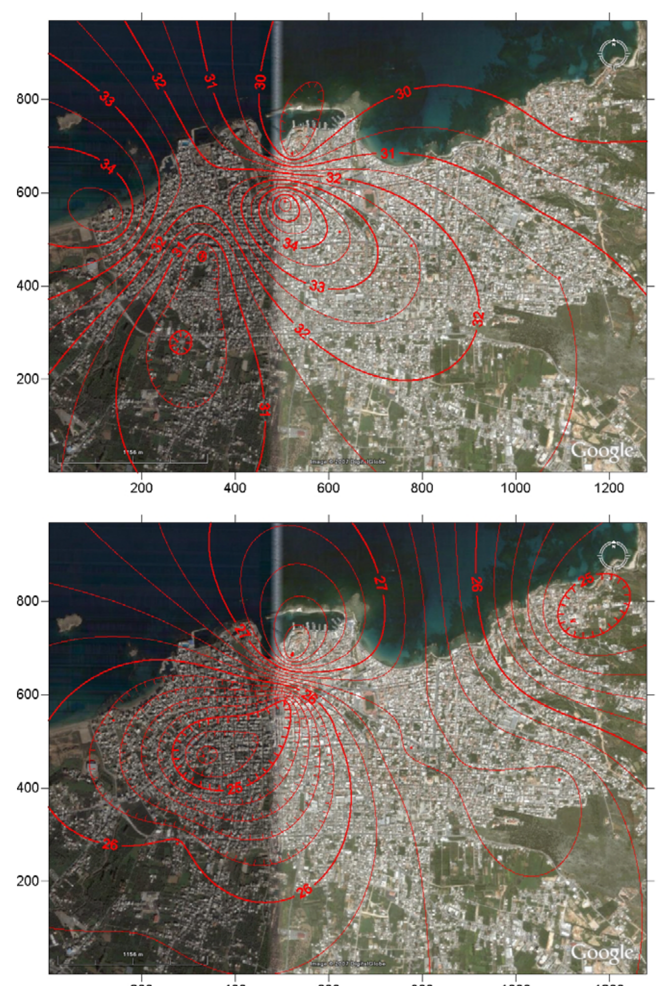

Fig. 11. The UHI in Hania during daytime (upper graph) and nighttime (lower graph) on 20/7/2007.

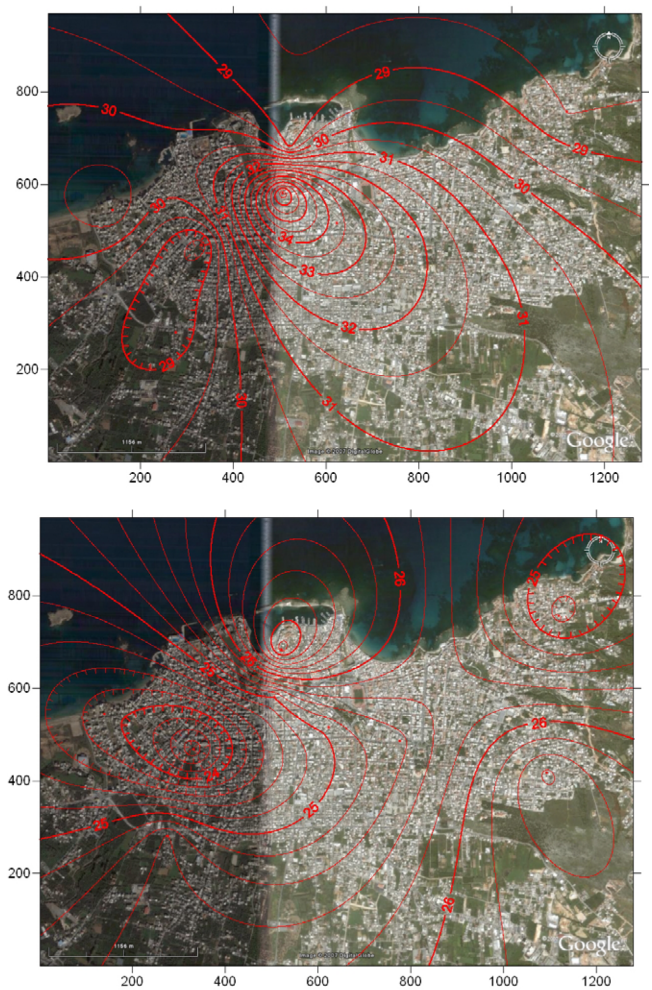

Fig. 12. The UHI in Hania during daytime (upper graph) and nighttime (lower graph) on 31/8/2007.

between 19:00 and 7:00. The highest temperatures during day are pinpointed for almost all days in station no 3 which is in a densely populated area in the city centre with limited vegetation. The highest temperatures of the day occur between 15:00–17:00. The UHI intensity is higher during day taking its maximum values that can be up to 8 °C for some cases. The UHI intensity is quite stable for all nights of the examined period fluctuating between 1.5 and 2 °C. Therefore the UHI is influencing the specific region during day while during night the differences are smoothed. This can be attributed to the local katabatic winds that are flowing down to the urban region from the White Mountains and decrease the heat stress.

4.3. Urban temperature routes

In the previous section the UHI structure and intensity is analytically investigated using the isotherms. In this specific section the temperatures on the main city's routes are recorded and presented. Despite the fact that the temperature routes are extracted by a small number of measuring locations, their illustration can indicate the places where possible mitigation techniques may be applied since the main city routes are suffering from emission of anthropogenic heat due to traffic. The routes are mapped in Fig. 13 and their characteristics are tabulated in Table 2. The temperature routes are created by Surfer software and for an indicative date (8th August 2007) are depicted in corresponding Figs. 14–18.

Fig. 13. Temperature routes plan.

All routes indicate that there is a temperature increment when moving towards the city centre. The temperature difference takes its maximum value of almost 3 °C in route no 1 which starts form the city centre (station no 3) and ends to the peripheral station no 9. A different profile can be seen in routes 3 and 6 which are traversing the city and are parallel to the northern coastal area. Routes 3 and 6 have a maximum temperature of 28.6 °C and 27.7 °C, respectively, which is gradually decreased when moving towards the suburbs. A significant temperature difference also occurs between the urban locations as depicted in Fig. 14. The urban temperatures in Dikastiria square (station no 4) are at least 1–1.5 °C lower than 1866 square (station no 3). This can be attributed to the fact that Dikastiria square is an open place with increased vegetation comparing to 1866 square.

Table 2
Routes characteristics.

No	Color	Route name	Length (m)
1	Red	Venizelou street	2150
2	Yellow	Dimokratias street	990
3	Blue	Botsari–Papanastasiou street	3072
4	Magenta	Apokoronou street	1073
5	Green	Kissamou street	1800
6	Orange	Gogoni street	2442

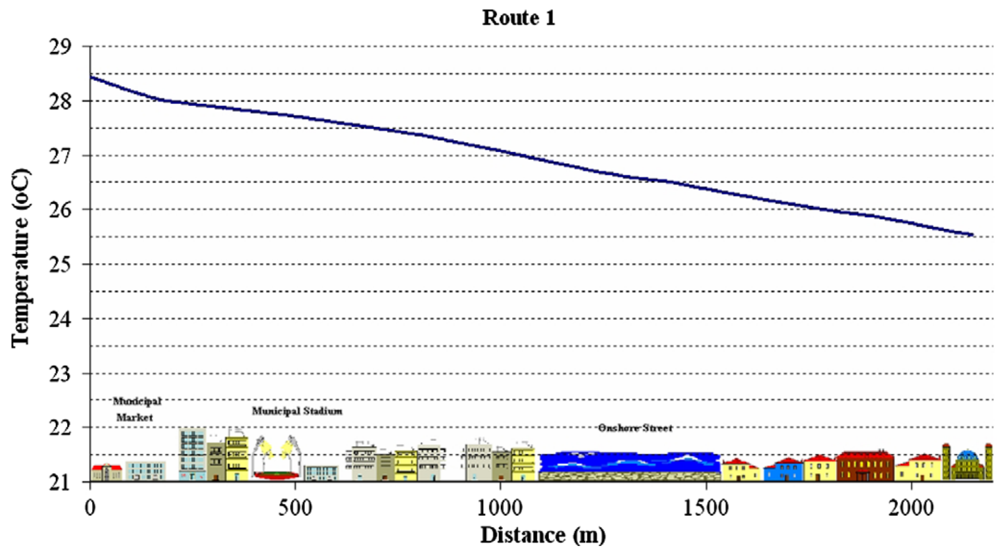

Fig. 14. Temperature values along Venizelou street (red line). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

4.4. Summer heat waves

The heat wave during summer 2007 in Hania, started on 23 June and lasted for 6 days, represents the peak values of Fig. 7. The isothermal layout during the hottest summer day (26/6/2007) is illustrated in Fig. 19. Temperatures vary from 37 to 43 °C, reaching a difference of 6 °C. Moreover, a thermal centre appears that is located at the city centre and affects almost the whole old city of Hania.

4.5. Influence of local meteorological conditions

Besides temperature and humidity measured at the eight urban stations and the temperature routes, the recorded data from the meteorological masts are utilised to identify correlations between the local and regional meteorological conditions and the urban heat island phenomenon in Hania.

4.5.1. Local wind field and UHI intensity

The Hania region's wind field was studied by Deligiorgi et al., 2007. The wind direction in the area varies from station to station due to differential local features (topography, altitude, orientation, distance from the shore, etc.). The predominant wind directions of the region are north and west as depicted in Fig. 20.

In the urban environment the density of buildings as well as the orientation of the main streets towards the wind patterns has a substantial impact on the UHI intensity. The majority of the main streets as depicted in Fig. 13 are

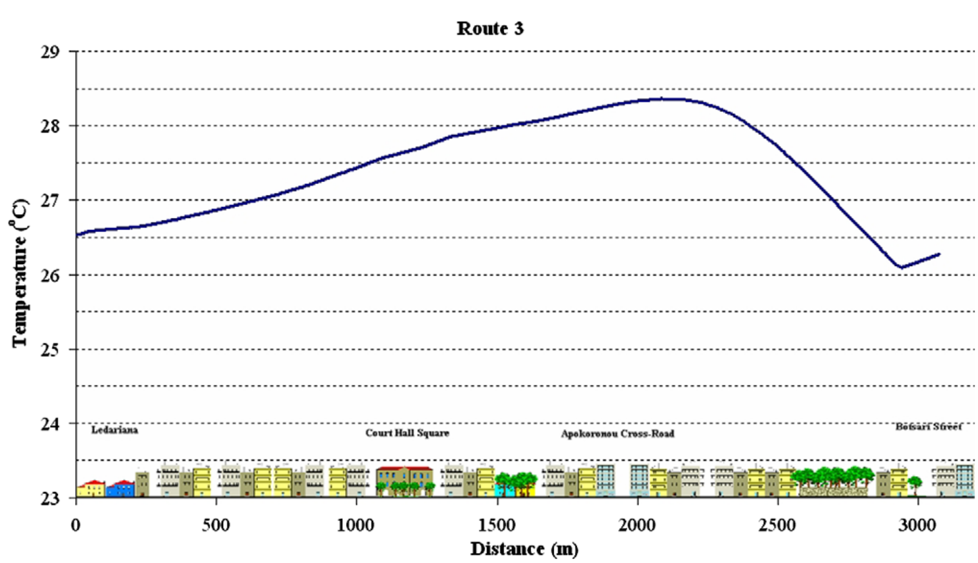

Fig. 15. Temperature values along Botsari–Papanastasiou street (blue line). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

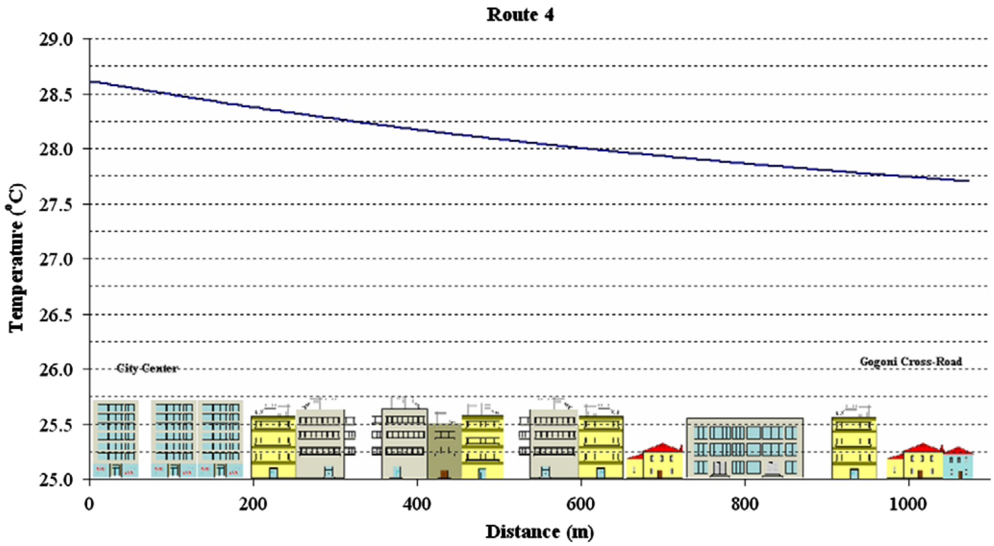

Fig. 16. Temperature values along Apokoronou street (magenta line). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

parallel or perpendicular to the costal line. Therefore the city layout generates a series of obstacles to the north or west winds' penetration as depicted by a yellow line in Figs. 21 and 22. Additionally, the old city's Venetian walls that are spread along the harbor invigorate even more the previously mentioned phenomenon. Although all wind patterns are studied versus their impact on UHI, only north and west wind fields are presented since they are the predominant ones. In Figs. 21 and 22, the wind direction is presented with blue arrows.

The UHI intensity when north winds are blowing is not remarkably changed. On the contrary western winds are more effective in reducing urban temperature differences due to main streets' orientation that supports urban natural ventilation. Thus, the western winds can reach the hot city spot and dissolve the temperature differences. Finally one significant difference between Figs. 20 and 21 is the region's maximum temperature position. Northern winds push the hot spot away from the coastal area while during western winds the maximum temperature is closer to the sea borders.

During late evening and night a strong influence in smoothing the temperature differences has the sea and land breeze in the suburban areas where the obstacles are not high (e.g., TEI location).

4.5.2. Impact of rainfall on UHI intensity

Although the Hania region is quite dry during summer periods, the recorded rainfalls clearly contribute to the minimisation of the UHI. More precisely, a normal-

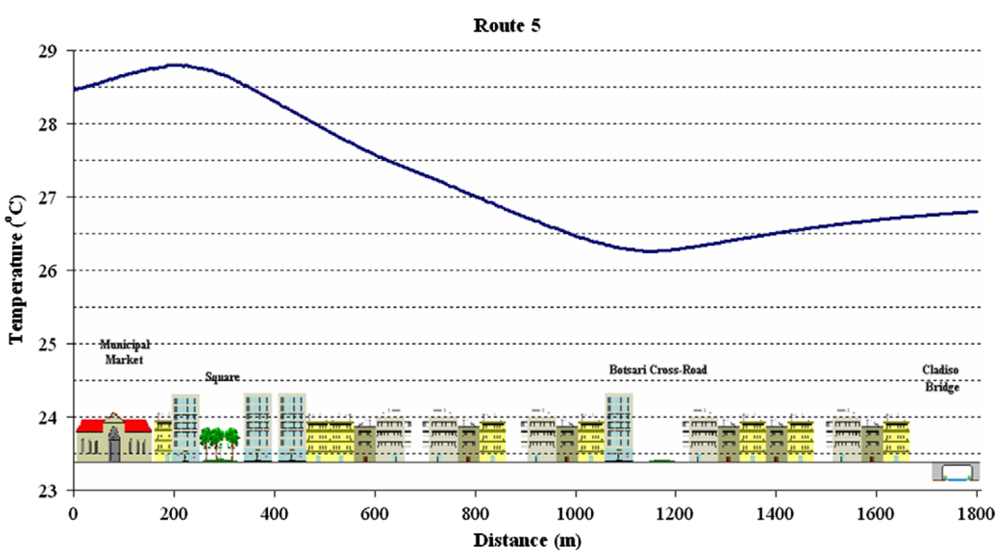

Fig. 17. Temperature values along Kissamou street (green line). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

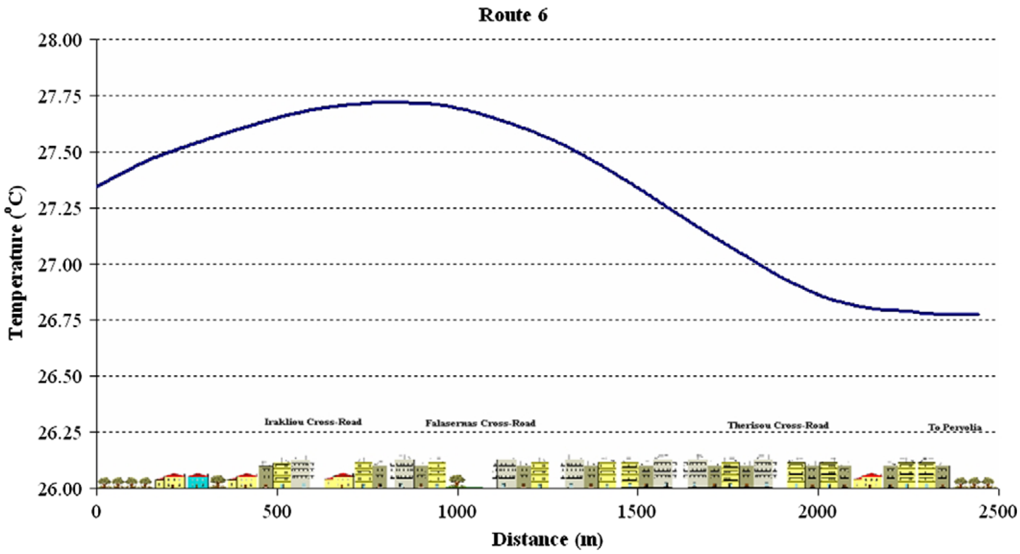

Fig. 18. Temperature values along Gogoni street (orange line). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

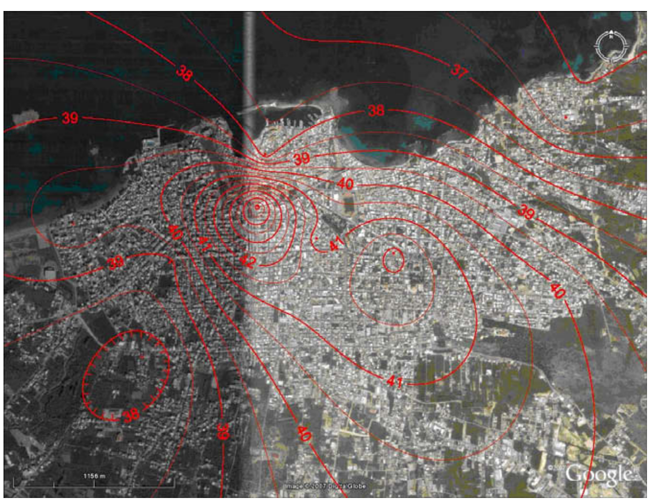

Fig. 19. The UHI form during heat wave on 27/6/2007 15:30.

ization of the temperature oscillations and profile is noticed as depicted in Fig. 23. Finally, UHI intensity remains approximately around 1–2 °C. In case of rainfalls, UHI is not characterised by any specific structure, while in areas that no rainfalls are occurred higher temperatures are recorded.

Moreover, DI values are also normalised in case of rainfalls occurrence, due to the fact that the whole region has similar meteorological conditions. During rainfalls there is no spatial distribution of temperature and relative humidity leading to almost constant DI for the whole area.

The relationship between the various meteorological conditions in the area and the urban heat island intensity is summarised in Table 3.

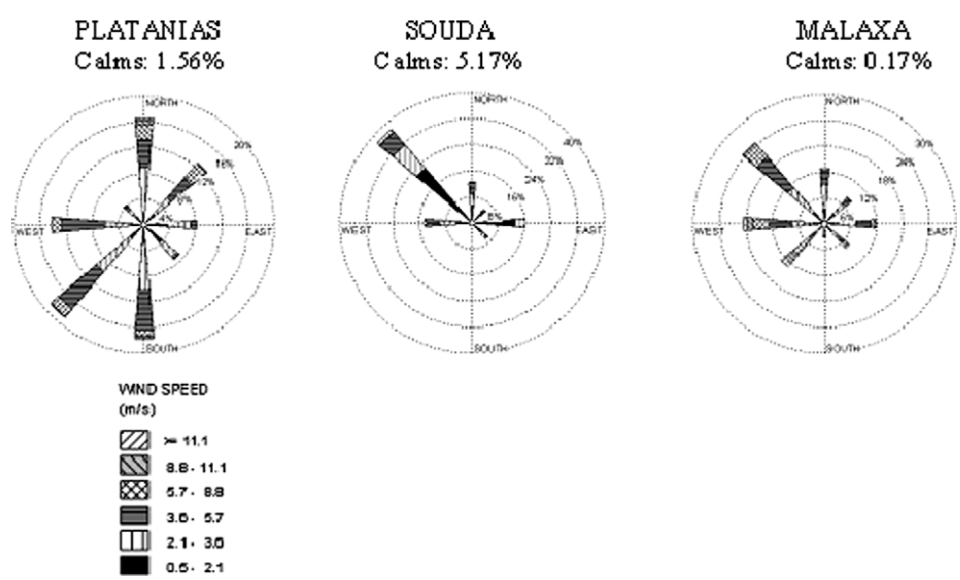

Fig. 20. The wind field of Hania (Deligiorgi et al., 2007).

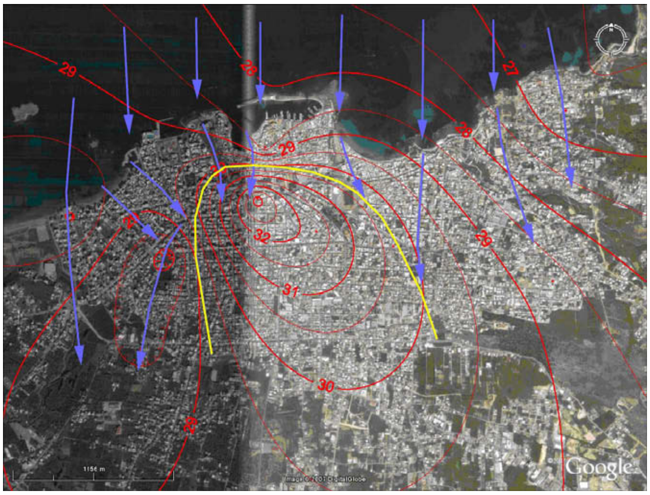

Fig. 21. UHI during north wind on 3/7/07.

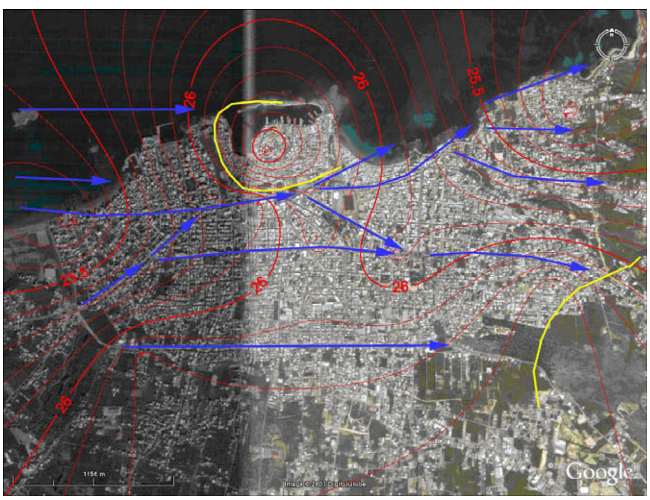

Fig. 22. UHI during west wind on 11/8/07.

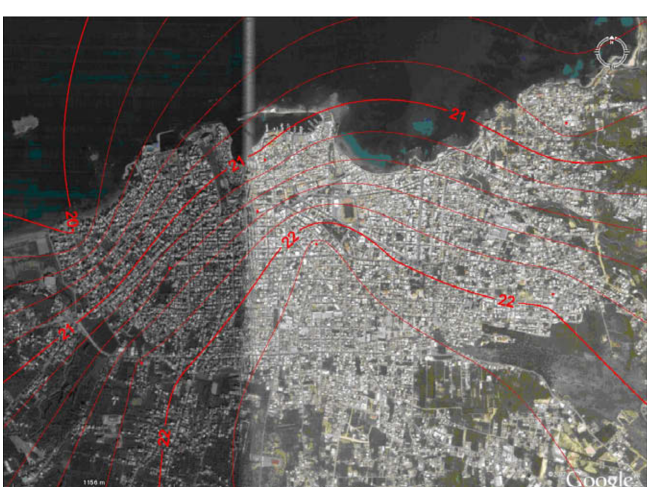

Fig. 23. Temperatures during rainfall.

Table 3
Correlation between UHI intensity and meteorological conditions.

No	Conditions	Correlation
1	North wind	Strong
2	West wind	Strong
3	Day and night	Strong
4	Rainfall	Medium
5	South wind	None
6	East wind	None

5. Conclusion

Heat island being the more documented phenomenon of climate change is usually expected to affect highly populated urban structures. The present study aimed to provide an additional quantitative analysis of the UHI existence in a coastal densely small Mediterranean town that was rapidly urbanised the last three decades.

Although Hania is a coastal medium sized city the UHI intensity during summer is evident and persistent. The outdoor comfort conditions deteriorate when moving from the coastal line and from the rural regions to the city centre. The hire rise buildings and the anthropogenic heat combined with the limited green spaces lead to a significant heat stress in the city centre comparing to the suburban and rural areas.

It remains now to future, more detailed investigations, to prove the ability of various mitigation techniques to the decrease of the phenomenon's intensity as indicated by the microclimatic conditions' differences among the various urban spots of the present study.

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