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ORIGINAL PAPER

Energy consumption based on heating/cooling degree days within the urban environment of Athens, Greece

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Abstract The degree-day method is considered to be a fundamental and a rather simple method to estimate heating and cooling energy demand. This study aims in a detailed and accurate assessment of cooling and heating degree days in different locations within the Greater Athens area (GAA), Greece. To achieve this goal, hourly values of air temperature from eight different locations within the GAA, covering the period 2001–2005, were used. Thus, the monthly and the annual number of cooling and heating degree days for each one of the examined locations could be estimated separately. Furthermore, an effort is made to evaluate the energy consumption for a specific building, based on the degree-day method, to indicate the impact of the canopy layer urban heat island on neighboring regions within the GAA. Results reveal that there is great spatial variability of energy demand and energy consumption along with significant differences in expenses for heating and cooling among neighboring regions within the GAA. Finally, regarding the energy demands of buildings, it is important to take into account intra-urban variability of canopy layer climates against an ensemble mean throughout the city, because the latter can result in inaccurate estimations and conclusions.

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1 Introduction

The rational utilization of energy, along with better management of environmental issues associated with energy consumption, results in cost reduction and maximized benefits for society. A simple and well-established tool for estimation of energy requirements is the heating/cooling degree-day method, which is based on outdoor air temperature measurements (ASHRAE 2001; Matzarakis and Balafoutis 2004; Christenson et al. 2006). The influence of ambient air temperature fluctuations on energy consumption is directly related to degree days and has been examined by various researchers (Sailor 2001; Valor et al. 2001; Pardo et al. 2002).

Heating degree days (HDDs) are calculated by simple subtractions of the outdoor temperature from the base temperature, taking into account only positive values. The base temperature is considered as the outdoor temperature above which there is no need for a building to be heated. Likewise, cooling degree days (CDDs) are calculated from temperatures above the base temperature. In this case, a base temperature is considered as the outdoor temperature below which a building needs no cooling. The calculation of degree days can be carried out by a number of ways and timescales (CIBSE 2006) as it appears below:

- Mean degree hours, calculated from the hourly temperature record
- Using daily maximum and minimum temperatures
- Using mean daily temperatures
- Direct calculation of monthly degree days from mean monthly temperature and the monthly standard deviation

During the last decades, studies on energy saving in buildings mainly focused on weather-related energy consumption. Guntermann (1982) introduced a degree-day formula that can be applied for industrial and commercial building computation purposes. The modified degree-day method, which is used primarily for residential buildings, utilizes the peak design heat loss divided by the design temperature difference. McMaster and Wilhelm (1997) in their paper refer that heat units, expressed in growing degree days (GDDs), are frequently used to describe the timing of biological processes. During past decades, different methods for the calculation of GDD have been proposed (Gilmore and Rogers 1958; Cross and Zuber 1972; Klepper et al. 1984; Russelle et al. 1984; Perry et al. 1986).

Martinaitis (1998) presents a method for the degree-day calculation, by means of the proposed cumulative air temperature duration function for the heating season, by additionally setting the temperature which determines the limits of the heating season in this function. The results of calculations received under the current climate conditions have been compared with the actual data. The degree days calculated on the basis of such functions, while analyzing the modes of operation of microclimate conditioning systems and simulating energy requirements for them, are very close to real climate conditions. The method proved to be acceptable and useful in solving energy consumption problems related to the building's life cycle. Christenson et al. (2006) studied the impact of climate warming on degree days and building's energy demand in Switzerland. They developed a procedure to estimate HDD and CDD from monthly temperature data that tested and applied to four representative Swiss locations. The findings showed that weather data currently used for building design increasingly lead to an overestimation of heating, and underestimation of cooling demand in buildings and, thus, periodic adaptation and consideration of local modifications, such as urban or topographic effects on temperature are required. Lowry (1977) discussed the problem of empirical estimation of urban effects on climate. He suggested a working model where the measured values of weather elements for a given weather type, time period, and station are taken to be linear sums of three components: the "background climate;" the effects of "local landscape," which is the departure of an observed value from background climate, due to landscape effects, such as topography and shorelines; and the effects of "local urbanization," which is the departure of the observed value from background climate, due to urban effects.

As far as Greece is concerned, during the last two decades, many researchers have dealt with the calculation of HDD and CDD, respectively, in urban environments. Concretely, Tselepidaki et al. (1994), in order to study the variability of the ambient temperature distribution in an urban environment, and the representativeness of a given station, calculated the CDD for three different meteorological stations located in the Greater Athens area (GAA). They proposed that it is possible to calculate the mean daily ambient temperature as a function of the maximum and minimum ambient temperature, using a linear regression formula. Matzarakis and Balafoutis (2004) calculated HDD by using daily maximum and minimum air temperature and then compared with an experimentally determined base air temperature equal to 14 °C, according to their estimations. These calculations are based on daily weather data from 40 meteorological stations belonging to the Hellenic National Weather Service. Papakostas and Kyriakis (2005) determined and presented heating and cooling degree hours for the two main cities in Greece, namely Athens and Thessaloniki, using hourly dry bulb temperature records from the meteorological stations of the National Observatory of Athens and of the Aristotle University of Thessaloniki. Stathopoulou et al. (2005) studied the relationship between midday land surface temperatures derived from satellite data and mean daily air temperature observations recorded at two standard meteorological stations in Athens City, Greece. The relationship is further used for the calculation of CDD. Gelegenis (2009) developed a simplified second-degree expression for the approximate estimation of annual HDD to various base temperatures. The only data needed for the application of this relation are the degree-day value to some reference base temperature and the mean annual temperature of the location. Papakostas et al. (2010) presented in their study the annual values of HDD and CDD for two typical base temperatures, namely 15 °C for heating and 24 °C for cooling, and for the two main cities of Greece (Athens and Thessaloniki), from 1983 to 2002. For the calculations, hourly dry bulb temperature records from the meteorological stations of the National Observatory of Athens and of the Aristotle University of Thessaloniki are used. The decade average (1983–1992 and 1993–2002) values of the HDD and CDD of the two examined cities are compared, for various base temperatures. The results showed that the average value of HDD of Athens for the decade 1993–2002, depending on the base temperature, is decreased from 8 to 22 % compared to the corresponding value for the decade 1983–1992. Similarly, the reduction in the Thessaloniki case is found in the range 4.5–9.5 %. The difference in the average value of CDD of the decades is more pronounced, the increase ranging from 25 to 69 % for Athens and from 10 to 21 % for Thessaloniki. In order to evaluate the effect of these changes on the energy requirements for heating and cooling of a typical residential building, the latter was calculated using the variable base degree-day method and the data sets of the two decades. The results showed a reduction of the heating energy demand by 11.5 and 5 % and an increase of the cooling energy demand by 26 and 10 %, for Athens and Thessaloniki, respectively.

Taking into consideration the aforementioned studies, it is clear that most of them refer to the calculation of HDD or CDD in one, two, or three at most areas of the GAA, a considerable extended Greek urban area with a population greater than three million (GSA 2012). This work aims in the assessment of HDD and CDD at eight different regions within the GAA. The stations were selected due to their different characteristics such as urban-traffic, urban-background, suburban-industrial, suburban-background, and suburban. Thus, a more detailed aspect of energy demands across the GAA is presented, with respect to the spatial variability of HDD/CDD values. In addition, we examine the energy consumption and CO_2 emission for heating and cooling, with respect to a hypothetical specific residential building installed in different microclimate neighboring locations within the GAA. However, there are some limitations concerning the performed analysis. The calculations in this paper assume that the only differences in the building's energy demand are due to the outdoor air temperature. The calculations of energy consumption, as well as CO_2 emission for heating and cooling, do not take into consideration factors such as among others, the shadowing from neighboring buildings, the wind, the radiation fluxes (solar receipt, longwave trapping), and landscape effects, such as topography and shorelines, as well. Urban obstacles and their orientation can influence thermal radiation consequently (Oke 1982; Givoni 1989; Mills 1999). The orientation of urban canyon surfaces and material of facing walls and floors modify air temperature and thermal stress, which is cooler/warmer during day/night (Nunez and Oke 1977; Santamouris et al. 1999). Shade enhancement from increased height-to-width (H/W) ratios is clearly capable of significant reductions in thermal stress and thus improves outdoor thermal comfort (Emmanuel et al. 2007; Ali-Toudert and Mayer 2007). Abreu-Harbich (2014) showed that urban design parameters such as width, height, and orientation modify thermal conditions within street canyons.

2 Data and methodology

In this study, the CDD and the HDD for eight different locations within the GAA were estimated for each month of the year, using hourly values of air temperature from eight different monitoring site stations within the GAA (Table 1).

The hourly air temperature data have been recorded by the monitoring network of the Hellenic Ministry of Environment, Energy and Climatic Change (HMEECC) for a 5-year period (2001–2005). Monitoring stations are classified due to their locations according to local climate zone (LCZ) scheme (Stewart and Oke 2012) (Table 1). The air temperature sensors (ROTRONIC PT100) were placed on a 10-m meteorological mast. In all cases, the meteorological mast is on the roof of a building except the case of Agia Paraskevi (AGP) where the mast was placed on the ground (Table 1). The completeness of air temperature data ranges from 96.2 % (AGP) up to 99.6 % (Patission, PAT) for the whole 5-year period 2001–2005. Figure 1 shows the position of the eight examined monitoring sites within the GAA.

The city of Athens is located in an area of complex topography within the Athens basin (~450 km^2). Mountains surround the city with heights ranging from 400 to 1500 m at the west, north, and east sides. Openings between these mountains exist at the northeast and at the west of the basin, while the sea extends southwards (Saronikos Gulf). The Athens basin has a southwest to northeast major axis and is bisected by a cluster of small hills (Larissi et al. 2010). According to 2011 demographic census, the GAA population is about 3.0 millions.

Considering the city center (PAT) as a starting point, the distances (linear distance in km) between the eight examined stations are presented in Table 1.

As mentioned above, there are a few different ways of calculating HDD and CDD, regarding the availability of data and the integrating period. The most accurate calculation is using hourly data ($0 \le k \le 24$) of outdoor air temperature (T_i) and integrating directly using the base temperature. Equations (1) and (2) show the calculation formulae of the daily values of HDD and CDD using hourly values of air temperature

$$\mathrm{HDD} = \frac{\sum_{i=1}^{k} T_{\mathrm{Hb}} - T_i}{24} \quad \mathrm{if}(T_{\mathrm{Hb}} - T_i) > 0, \quad 0 \le k \le 24 \tag{1}$$

$$\mathrm{CDD} = \frac{\sum_{i=1}^{k} (T_i - T_{\mathrm{Cb}})}{24} \quad \mathrm{if}(T_i - T_{\mathrm{Cb}}) > 0 \quad 0 \le k \le 24 \tag{2}$$

where T_{Hb} and T_{Cb} are the corresponding base temperature for HDD and CDD, respectively. For each month of the year, the daily values are summed giving the monthly values of CDD and HDD and, in the process, the annual values of CDD and HDD are estimated. As base temperature, the thresholds 26 and 18 °C were considered for the calculation of CDD and HDD, respectively. This choice was based on the technical directive issued by the Technical Chamber of Greece, which is responsible for technical issues, including building's energy requirements. According to this technical directive, in order to calculate the building's energy performance for the issuance of the certificate of energy efficiency, the aforementioned values are defined as the base temperature for the HDD and CDD (Technical Chamber of Greece 2010).

Table 1 Stations used in the study and related information

Station	Abbreviated station name	LCZ scheme	Longitude	Latitude	A[a]	B[b]	C[c]	D[d]
Agia Paraskevi	AGP	9	37° 59′ 42″	23° 49′ 10″	290	10	8.0	NE
Galatsi	GAL	2	38° 01′ 13″	23° 44′ 53″	145	20	2.7	NE
Geoponiki	GEO	5	37° 59′ 01″	23° 42′ 25″	145	20	2.9	SW
Liossia	LIO	6	38° 04′ 36″	23° 41′ 52″	165	17	9.8	NW
Lykovrisi	LYK	6	38° 04′ 11″	23° 46′ 35″	210	13	9.3	NNE
Marousi	MAR	3	38° 01′ 51″	23° 47′ 14″	145	17	6.4	NE
Patission	PAT	2	37° 59′ 57″	23° 43′ 59″	105	30	–	–
Thrakomakedones	THR	9	38° 08′ 37″	23° 45′ 29″	550	13	16.5	N

[a] Station height (m.a.s.l.)

[b] Air temperature sensor height above ground level (m)

[c] The distances (linear distance in km) between the eight examined stations and the city center (PAT)

[d] Spatial orientation in relation to the city center (PAT)

The annual energy consumption for heating purpose Q_h (kWh) for a given building, assuming that the building is heated continuously, could be written as (Kolokotroni et al. 2010)

$$Q_h = \frac{U' \cdot \text{AHDD} \cdot 24}{\eta} \tag{3}$$

where U' denotes the overall building heat loss coefficient (kW K^{-1}), AHDD denotes the annual sum of HDD (°C day), multiplied by 24 (hours per day) to convert to hours, while η is the coefficient of efficiency of the internal heat sources ($0<\eta<1$). The overall building heat loss coefficient U' is given by

$$U' = \frac{A \cdot U + \frac{1}{3} \cdot N \cdot V}{1000} \tag{4}$$

where U is the fabric U value (W m^{-2} K^{-1}), A is the component area (m^2), N is the air infiltration rate in air changes per hour (h^{-1}), and V is the volume of the space (m^3). The numerical factor (1/3) arises from typical values of density and specific heat of air and the conversion to air changes per hour (CIBSE 2006). The second part of the Eq. (4) represents the natural ventilation heat losses; therefore, the numerical factor (1/3) arises from the product of specific heat of air C_P and the air density ρ_a. By assigning typical values, the corresponding numerical value is determined by the following calculation:

$$d \cdot C_P = \left[1.2 \frac{\text{kg}}{\text{m}^3}\right] \times \left[1.005 \frac{\text{kJ}}{\text{kg} \cdot \text{K}} \cdot \frac{1}{3600} \frac{\text{kW} \cdot \text{h}}{\text{kJ}} \cdot \frac{\text{W}}{\text{kW}}\right] = 0.335 \frac{\text{W} \cdot \text{h}}{\text{m}^3 \cdot \text{K}} \approx \frac{1}{3} \frac{\text{W} \cdot \text{h}}{\text{m}^3 \cdot \text{K}} \tag{5}$$

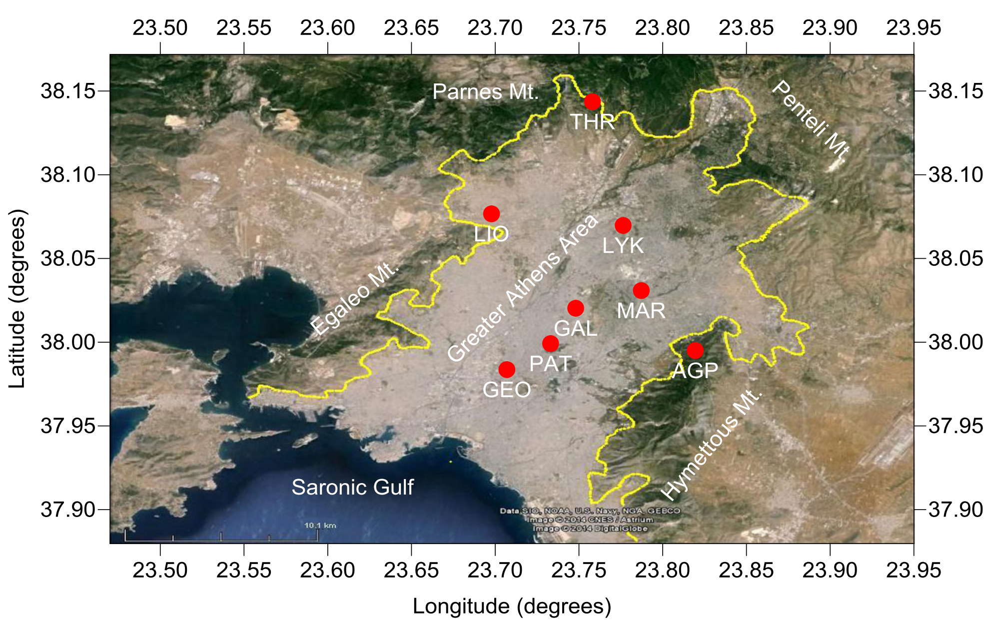

Fig. 1 Network of the stations within GAA, used in the study

Respectively, the annual energy consumption for cooling purpose Q_c (kWh) for a given building may be written as

$$Q_c = \frac{\dot{m} \cdot C_P \cdot \mathrm{ACDD} \cdot 24}{\mathrm{COP}} \tag{6}$$

where denotes the mass flow rate of kilogram of air that is cooled per second (kg s^{-1}), C_P is the specific heat of air (kJ kg^{-1} K^{-1}), ACDD is the annual sum of CDD (Kday) multiplied by 24 h day^{-1}, and finally, COP is the coefficient of performance of the cooling unit. COP is the efficiency ratio of the amount of heating or cooling provided by a heating or cooling unit to the energy consumed by the system. Both the annual heating energy consumption and the annual cooling energy consumption have to be transformed into primary energy consumption (PEC), in order to be compared. Primary energy consumption refers to the direct use at the source, that is, energy that has not been subjected to any conversion or transformation process. In each case, the following equation is used:

$$\mathrm{PEC} = Q \cdot a \tag{7}$$

where Q is the total annual cooling or heating energy consumption (kWh) and a is the primary energy conversion factor, respectively (dimensionless number). The PEC factor a takes different values depending on fuel. Also, it changes with time because it depends on the generating mix in any given time period.

3 Results

3.1 Analysis of HDD and CDD variation within the GAA

The first Hellenic building thermal insulation regulation (HBTIR) took effect in 1980, setting the minimum requirements for thermal transmission of the building envelope for different climate zones in Greece. HBTIR was replaced by a new national regulation on the energy assessment of buildings, which is known as KENAK in April 2010 (Dascalaki et al. 2011). In line with KENAK, there are four climate zones defined on the basis of the HDD. The annual numbers of HDD (°C day) range from 601 to 1100 for climate zone I, from 1101 to 1600 for climate zone II, from 1601 to 2200 for climate zone III, and from 2201 to 2620 for climate zone IV.

Table 2 presents the mean monthly values as well as the annual values of both HDD and CDD, for each one of the eight examined regions within the GAA resulted from hourly temperatures covering the time period 2001–2005. Positive differences ($T_{\mathrm{Hb}} - T_i > 0$) are observed from October to May (cold period of the year), while positive differences ($T_i - T_{\mathrm{Cb}} > 0$) are observed from May to October (warm period of the year).

According to Table 4, for the city center (PAT), the annual number of HDD is about three times lower than the corresponding number of the suburban-background region of Thrakomakedones (THR). In addition, it seems that three different microclimate zones appear within the GAA (Table 2). Stations PAT, Galatsi (GAL), and Geoponiki (GEO) (from 0 to 3 km around the city center) belong to the zone I; stations Marousi (MAR), Liossia (LIO), AGP, and Lykovrisi (LYK) (from 6 km up to 10 km around the city center) belong to zone II, while THR station belongs to the upper limit of zone III (16.5 km north to the city center).

Furthermore and according to Table 4, the annual number of CDD for the city center (PAT) is about seven times higher than the corresponding number of the suburban-background region of THR. It is obvious that during the warm period of the year, the energy demand for cooling for a given building is greater at the city center (PAT) than the peripheral areas (THR), as it was expected.

Throughout the examined period in all stations, the values of HDD on daily basis range from 0 to 25.4 °C day. In the process, the frequency distribution of HDD values was examined, taking into account six equivalence classes (class range of 5 °C day). Results are presented in Table 3. It seems that for the stations, which are close to the city center (PAT, GEO, and GAL), 61.9 to 73.3 % of the HDD values are less than 5 °C, against 43.9 to 58.4 % for the peripheral stations. This means that the requirements for heating in areas, which are close to the city center, are lower compared to those in the suburbs.

Regarding CDD, they vary from 0 to 9 °C day, so five equivalence classes (range of 2 °C day) were selected for the interpretation of the frequency distribution of CDD. Results are presented in Table 4, depicting that for the peripheral stations (MAR, LIO, LYK, AGP, and THR), 70.1 to 94.8 % of the CDD values are less than 2 °C day. Thus, the energy requirements for cooling are not so high against those of the stations, which are close to the city center (PAT, GEO, and GAL).

For each one of the eight examined stations within the GAA, the mean value of HDD, the standard deviation, as well as the outliers (minimum and maximum value) for the period 2001–2005 were calculated. Results are presented in Fig. 2, indicating that the absolute maximum value (whiskers), the standard deviation (box), and the mean value (center of the box) of HDD are increasing as we move away from the city center to the suburbs.

The same methodology was also applied to CDD time series. Results are presented in Fig. 3, indicating that moving from the periphery to the city center, the mean value of CDD is increasing along with the absolute maximum value outlier and the standard deviation. These give evidence that the

Table 2 Mean monthly values of HDD (°C day) (base temperature 18 °C) and mean monthly values of CDD (°C day) (base temperature 26 °C) during the period 2001–2005

		PAT	GAL	GEO	MAR	LIO	AGP	LYK	THR	GAA mean
January	HDD	181	230	227	252	283	272	310	387	268
	CDD									
February	HDD	184	224	220	243	269	274	294	362	259
	CDD									
March	HDD	121	158	156	177	195	198	223	302	191
	CDD									
April	HDD	59	92	85	107	128	133	149	219	122
	CDD									
May	HDD	2	7	7	12	24	21	34	71	22
	CDD	8	6	4	5	5	3	4	1	4
June	HDD									
	CDD	63	45	42	37	35	26	25	7	35
July	HDD									
	CDD	133	98	93	87	76	64	61	24	79
August	HDD									
	CDD	123	98	88	76	69	58	53	19	73
September	HDD									
	CDD	27	17	15	14	11	9	8	3	13
October	HDD	9	19	22	27	46	36	61	111	41
	CDD	4	2	2	2	1	1	1		2
November	HDD	62	98	104	118	158	137	175	261	139
	CDD									
December	HDD	17	214	228	237	287	265	308	412	265
	CDD									
Annual sum	HDD	787	1043	1049	1174	1390	1335	1555	2126	1307
	CDD	357	265	244	220	198	162	152	54	206

energy requirements for cooling are different and higher inside and close to the city center than the suburbs.

For the visualization of the spatial variation of HDD and CDD within the GAA, we used classed post maps instead of applying the interpolation technique, because of the small number of data sets, in order to identify different ranges of data by assigning a different symbol and proportional size to each data range, with respect to each one of the eight sample locations.

Figure 4a depicts the spatial distribution of the annual number of HDD within the GAA. During the cold season of the year, the energy needs for heating are very high for the north suburban areas compared to the corresponding needs for the areas close to the city center.

Figure 4b depicts the spatial distribution of the annual number of CDD within the GAA. It seems that the canopy layer urban heat island effect plays a key role by modifying the microclimate conditions in neighboring regions, within the

Table 3 HDD frequency distribution during the period 2001–2005

HDD (°C day)	PAT (%)	GEO (%)	GAL (%)	MAR (%)	AGP (%)	LIO (%)	LYK (%)	THR (%)
0<HDD≤5	73.3	62.9	61.9	58.4	51.8	48.7	43.9	29.1
5<HDD≤10	20.5	27.9	28.2	29.3	31.5	34.3	33.6	31.1
10<HDD≤15	5.6	8.3	8.9	10.8	14.2	14.8	18.1	25.5
15<HDD≤20	0.6	0.8	0.9	1.4	2.2	1.9	4.2	11.8
20<HDD≤25		0.1	0.1	0.1	0.3	0.3	0.3	2.4
25<HDD≤30								0.1
Total	100	100	100	100	100	100	100	100

Table 4 CDD frequency distribution during the period 2001–2005

CDD (°C day)	THR (%)	LYK (%)	AGP (%)	LIO (%)	MAR (%)	GEO (%)	GAL (%)	PAT (%)
0<CDD≤2	94.8	81.8	81.5	74.7	70.1	66.6	62.6	52.0
2<CDD≤4	5.0	14.4	13.9	17.9	21.0	21.5	24.9	24.7
4<CDD≤6	0.2	3.7	4.4	6.9	8.2	9.7	10.2	15.8
6<CDD≤8		0.1	0.2	0.5	0.7	1.9	2.2	6.7
8<CDD≤10						0.3	0.1	0.8
Total	100	100	100	100	100	100	100	100

GAA. Philandras et al. (1999) studied the urban heat island (UHI) in Athens and concluded that the urbanization effect refers mainly to the maximum air temperature (an increase of ~2 K) and to the warmer seasons of the year. The minimum air temperature time series do not display any significant trend. The UHI is mainly attributed to the extensive building of Athens after the Second World War and the rapid increase of the population and the number of vehicles mainly after 1970. Nastos and Matzarakis (2008) who studied the tropical days (days with daily maximum air temperature greater than 35 °C) over Greece found that the annual number of tropical days in Athens during the last decade of the twentieth century appeared to have overcome the limit of mean +2×standard deviation. Recently, in their work in Athens, Matzarakis and Nastos (2011) concluded that a statistically significant (at 95 % confidence level) increasing trend of the maximum duration of heat waves within the year (b=1.33 days/year, p=0.00001) is observed since 1983. In addition, the number of heat waves (HWs) within the year appears to be a statistically significant (at confidence level 95 %) trend (b=0.26 HW/year, p=0.00001), since 1983.

As it appears in Fig. 4b, a very warm area in the center of the GAA is established, while the number of CDD is reduced far from the city center. It is worth noting that this decrease is rather great in just a few kilometers away from the city center. Even during the cold season of the year, microclimatic conditions have been established more likely due to the phenomenon of canopy layer urban heat island effect. In any case and according to the above analysis, for both HDD and CDD, a significant spatial dispersion of their values between neighboring regions within the GAA is evident, indicating a corresponding variance of energy demand in building sector. In order to highlight and interpret further the spatial variance of energy demand within the GAA, a case study regarding the estimation of energy requirements for a specific building is then presented. At this point, it should be emphasized that an indicative approximate calculation of energy consumption will be described in the following section. The purpose of this study is to highlight the differences on energy consumption between neighboring areas within the GAA, due to the canopy layer urban heat island.

3.2 Estimation of energy consumption and CO_2 emission for heating and cooling in a given building

In this section, a hypothetical residential building is assumed as a detached house (representative single family home) with an area of about 120 m^2, inhabited all year and continually heated/cooled during the cold/warm period of the year. The external walls of the house have polystyrene insulation, while

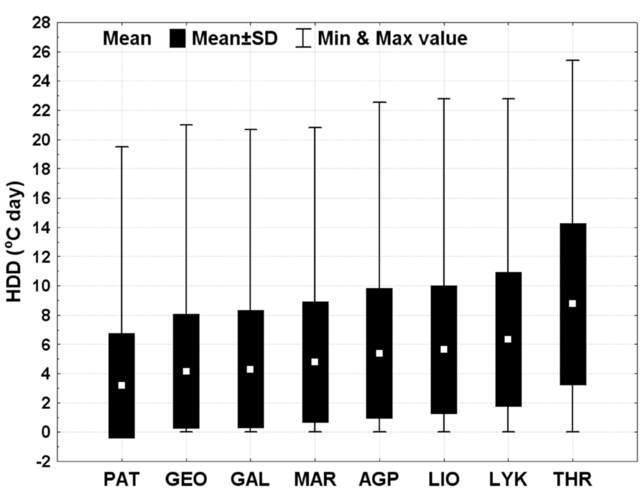

Fig. 2 Box and whisker plots of HDD (°C day) during the period 2001–2005

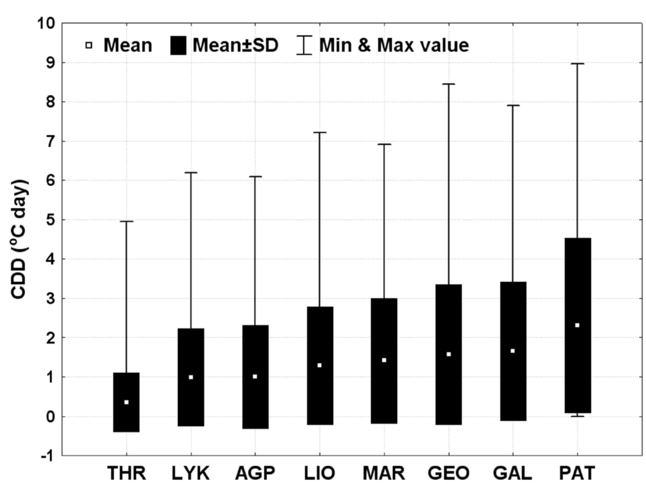

Fig. 3 Box and whisker plots of CDD (°C day) during the period 2001–2005

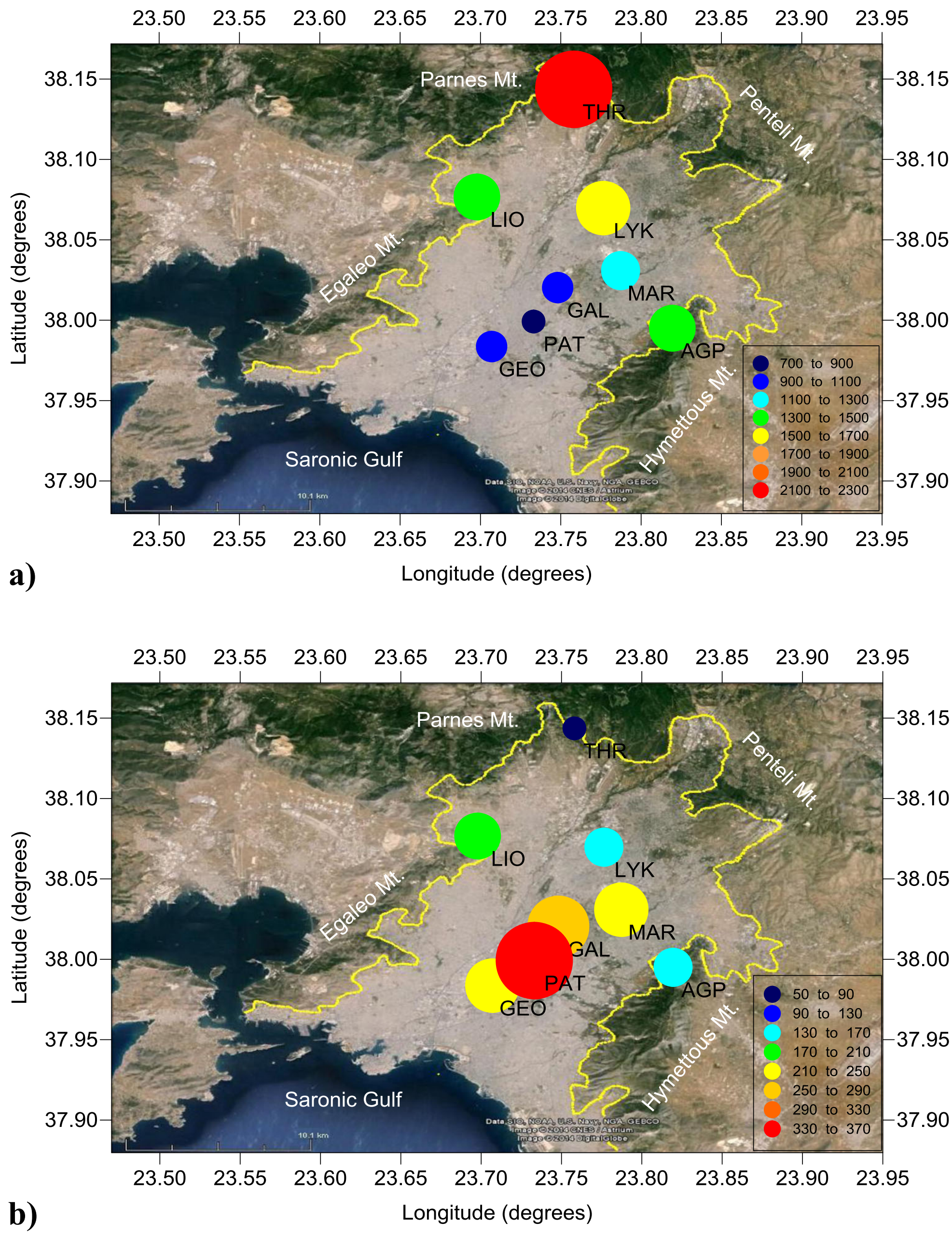

Fig. 4 Spatial distribution of the annual HDD (a) and CDD (b) (°C day) within GAA for the period 2001–2005

all the windows are from aluminum panels with double glass (typical insulation and construction of the houses within the GAA). This specific detached house in any case uses for heating an oil boiler and for cooling five inverter electrical air-conditioning units about 12,000 BTU each one and has a typical thermal insulation (as a great majority of the houses within the GAA). For that building, in each one of the eight examined sites within the GAA, the energy consumption with respect to the heating and cooling degree-day method is calculated by applying the aforementioned Eqs. (4), (5), (6), and (7). The values of all the necessary parameters used in Eqs. (4), (5), (6), and (7) are considered as follows (CIBSE 2006; Balaras et al. 2007; Dascalaki et al. 2011):

For the calculation of the annual heating energy consumption Q_h (kWh), U' which denotes the total heat loss coefficient is considered equal to 0.350 kW K^{-1}, while the coefficient of efficiency η of the internal heat sources (oil boiler) is considered equal to a typical mean value of 0.9. Respectively, for the calculation of the annual cooling energy consumption Q_c (kWh), the mass flow rate for a specific cooling unit of about 12,000 BTU (air-conditioning unit) is considered equal to = 0.109 kg s^{-3}. The specific heat of air is considered equal to

C_P=1.005 kJ kg^{-1} K^{-1}, and the coefficient of performance of the cooling units is equal to 3.5, which represents a typical mean COP value.

The annual heating and cooling energy consumption is transformed to primary energy consumption using the relationship (7), in order to be compared. In the case of heating (the used fuel is oil), the primary energy conversion factor a is equal to 1.1 while in cooling (electrical air-conditioning units), it is equal to 2.9. In both cases, the aforementioned values of the conversion factor a are generated by the energy mix of Greece (Technical Chamber of Greece 2010). Table 5 presents the annual heating energy consumption (AHEC) and the annual cooling energy consumption (ACEC), calculated according to the HDD and CDD method for the specific aforementioned house, in each one of the eight examined sites within the GAA in kWh per square meter of the aforementioned residential building. High spatial variability for both AHEC and ACEC appears; namely, AHEC ranges from 61.21 kWh m^{-2} (PAT) up to 165.36 kWh m^{-2} (THR), against ACEC, which ranges from 1.72 kWh m^{-2} (THR) up to 11.34 kWh m^{-2} (PAT).

Figure 5 depicts the primary energy consumption (%) for heating (PHEC) and cooling (PCEC) purposes for the specific house within the GAA. On one hand, when this house is located in the city center (PAT), it needs about 65 % of the total annual energy for heating and the rest 35 % for cooling, while on the other hand, when it is located at the suburban area of THR, it needs more than 95 % for heating and only about 5 % for cooling. This pattern indicates a significant spatial variance of energy consumption within the GAA and a great range of energy consumption values for heating and cooling purposes, respectively.

In order to examine the contribution of CO_2 emissions with respect to the primary energy consumption in each one of the eight examined sites within the GAA, the carbon dioxide equivalent (CO_2-eq) is estimated. CO_2-eq is a metric measure used to compare the emissions from various greenhouse gases on the basis of their global warming potential, by converting the mass of other gases to the equivalent mass of carbon dioxide with the same global warming potential (IPCC 2007). For the Greek case (energy mix), the coefficient of emission is considered to be 0.264 kg CO_2-eq kWh^{-1} regarding heating energy consumption (oil boiler) and 0.989 kg CO_2-eq kWh^{-1} regarding cooling energy consumption (electrical air-conditioning units), according to the Technical Camber of Greece (2010). Figure 6 depicts the percentages of the annual CO_2-eq emission (kg) with respect to AHEC and ACEC for the specific house at the eight different sites of the GAA. It seems that CO_2 emission varies highly within the GAA in relation to the type of energy consumption. Specifically, almost 35/65 % of CO_2-eq emission is due to heating/cooling, at the city center (PAT) against 90/10 % of CO_2-eq emission due to heating/cooling, at the suburban area (THR).

Table 6 (A) presents the differences (%) of the annual PEC between the city center (PAT) and the other seven examined sites within the GAA. Taking as zero base the value of annual PEC at city center (PAT), which is the lowest value of the entire annual PEC values that appear within the GAA, the differences (%) with respect to the city center is then calculated and depicted in Table 6 (A). It seems that for the specific house, when it is located at the suburban area of THR, 16.5 km away from the city center (PAT) and 450 m above the city center altitude level, a high difference (86.5 %) of annual PEC with respect to the city center exists. In other words, the specific house consumes almost the double annual PEC installed at the suburban area against the city center. Furthermore, Table 6 (B) depicts the differences (%) of CO_2-eq emission among the eight examined sites within the GAA, taking as zero base the value of annual CO_2-eq emission at AGP station, which is the lowest value of the annual CO_2-eq emissions that appear within the GAA. The differences of CO_2-eq emissions range from 0 % (AGP) up to 17.9 % at the suburban region of THR, indicating that at AGP monitoring site, the energy mix causes the lowest CO_2-eq emission compared to those of the other seven examined sites within the GAA.

3.3 Analysis of the economic cost of cooling and heating energy consumption

The calorific value of oil is taken which is equal to 10 kWh l^{-1} of oil (a mean oil density is equal to 845 kg m^{-3}, and a calorific value of 11.9 kWh kg^{-1} is considered). This means that ideally 1 l of oil yields 10 kWh of heat energy. However, the final heat depends on the efficiency of the oil boiler. Assuming a typical mean value of 90 % efficiency, 0.111 l of oil consumption is required for each kWh of heat. Besides, taking into account the oil prices (2013) for heating in Greece, the mean annual cost of oil consumption is about 1.25 € per liter of oil, meaning that the cost is about 0.138 €kWh^{-1} for each kWh of heat produced by oil. According to the Hellenic Public Power Corporation, the cost per kWh of electricity consumption is approximately 0.133 €kWh^{-1}. This price is considered for household bills (in 2013 prices) and concerns an average electrical energy consumption of about 2000 kWh in a time period of four consecutive months. Considering the above, the cost per kWh of electricity consumption for cooling, the cost per kWh of oil energy consumption for heating, and the total annual cost of energy consumption are then calculated for the specific hypothetical house installed in each one of the eight examined sites within the GAA. Table 6 (C) depicts the annual cost per square meter (€m^{-2}) of heating energy consumption (ACHEC) and the annual cost per square meter (€m^{-2}) (D) of cooling energy consumption (ACCEC) for the given detached

Table 5 Annual heating energy consumption (AHEC) and annual cooling energy consumption (ACEC)

	PAT	GAL	GEO	MAR	AGP	LIO	LYK	THR
AHEC (kWh/m^2)	61.21	81.13	81.59	91.31	103.83	108.11	122.09	165.36
ACEC (kWh/m^2)	11.34	8.42	7.75	6.99	5.15	6.30	4.83	1.72
Total (kWh/m^2)	72.55	89.55	89.34	98.3	108.98	114.41	126.92	167.08

house at the eight examined regions within the GAA. ACHEC ranges from 8.49 €m^{-2} up to 22.94 €m^{-2} between the city center (PAT) and the suburban site (THR), respectively. This means that the same house costs 2.7 times more in heating when it is located at the suburban area of THR against the city center. The same conclusions arise concerning the annual cost of energy consumption (both for heating and cooling), which is about 2.3 times more in the peripheral areas than in the center of the city. Finally, the annual cost for cooling purpose ranges from 0.23 €m^{-2} at the suburban area of THR up to 1.51 €m^{-2} in the city center (PAT).

Taking as zero base the annual cost of energy consumption (ACEC) at PAT station (city center), which is the lowest cost of ACEC values appeared within the GAA, the ACEC differences (%) are then calculated with respect to the city center and depicted in Fig. 7.

It seems that there is a great difference of the ACEC (131.7 %), when the specific house is located at the suburban site (THR), meaning that the specific house costs more than twofold in price for both heating and cooling during the year at the suburban area compared to the city center.

4 Discussion

The residential buildings in Greece account for 25 % of the total energy consumption and consume 32.7 % of the total electricity generated in the country and 21.5 % of the total thermal energy (EC 2004; HMD 2004; Balaras et al. 2007). Energy consumption in residential buildings represents 73.6 % of the total energy consumed by the Hellenic building sector (Balaras et al. 2007). The effect of the meteorological conditions on the electricity demand is of high concern (Pardo et al. 2002; Psiloglou et al. 2009). Mirasgedis et al. (2006), who developed and tested appropriate forecasting tools for the electricity demand in Greece, concluded that the influence of the extreme weather appears to amount to about 4–4.5 % above an expected demand increase.

Our study constitutes the first approach to energy consumption in the residential building sector within GAA, by applying HDD and CDD method. In a similar study, Kolokotroni et al. (2010) found that during January and February, there is a difference of about 70 and 50 °C day respectively, between the city center of London, UK, and the suburban areas of London. It was observed that depending on the severity of the weather (as indicated by the degree days), heating energy consumption in central London is 65–85 % of the heating required for the same building based outside the London's urban heat island (UHI). Cooling energy consumption is 32–42 % higher than cooling energy required for the same building based outside the aforementioned area. In our study, it was found that during January and February, there is a difference of about 200 and 180 °C day, respectively, between the Athens' city center (PAT) and the suburban area of Thrakomakedones (THR). Besides, on one hand, heating energy consumption in the center of GAA is 37–75 % of the heating required for the same building installed outside the Athens' UHI. On the other hand, cooling energy consumption is 25–85 % higher than cooling energy required for the same building based outside the Athens' UHI. A great variability of PEC values appears among neighboring regions within the GAA. Furthermore, the CO_2 emissions due to PEC show a

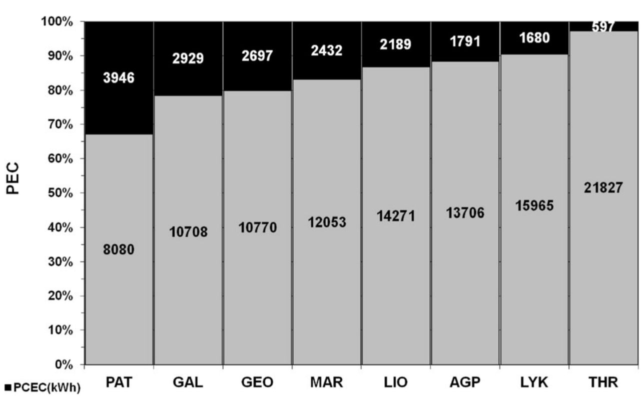

Fig. 5 Primary energy consumption (%) for heating (PHEC) and cooling (PCEC) purposes for all examined sites

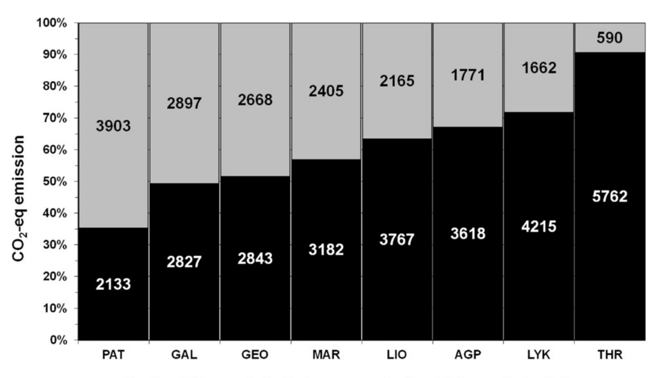

Fig. 6 CO_2-eq emission (%) for each type of energy consumption

Table 6 Differences of the annual primary energy consumption percentages and CO_2-eq emission percentage and the annual cost of heating energy consumption, the annual cost of cooling energy consumption, and the total annual cost of energy consumption for cooling and heating purposes

	PAT	GEO	GAL	MAR	AGP	LIO	LYK	THR
A[a] (%)	0.0	12.0	13.4	20.4	28.9	36.9	46.7	86.5
B[b] (%)	12.0	2.2	6.2	3.7	0.0	10.0	9.0	17.9
C[c]	8.49	11.32	11.26	12.67	14.41	15.00	16.78	22.94
D[d]	1.51	1.03	1.12	0.93	0.68	0.83	0.64	0.23
E[e]	10.00	12.35	12.38	13.60	15.09	15.83	17.42	23.17

[a] Differences of the annual primary energy consumption percentages between the city center (PAT) and the other seven examined areas within the GAA

[b] CO_2-eq emission percentage differences between the eight examined regions within the GAA

[c] Annual cost of heating energy consumption (€m^{-2})

[d] Annual cost of cooling energy consumption (€m^{-2})

[e] Total annual cost of energy consumption for cooling and heating purposes (€m^{-2})

great variation, indicating that the differences among the eight examined regions within the GAA reach 17.9 % at the suburban area of Thrakomakedones against the lowest value of CO_2 emission in Agia Paraskevi. Finally, more than twofold money for both heating and cooling during the year is needed in the suburban area (THR) against the city center (PAT), with respect to the same specific house.

In order to investigate the prevailing meteorological conditions during cold and heat waves across the GAA, the coldest and the hottest day during the examined period 2001–2005 was studied respectively. February 13, 2004 was found to be the coldest day of the period 2001–2005 within GAA. We verified our results by analyzing the synoptic weather conditions, which had been established over the wider area of Greece on that day, based on US National Centers for Environmental Prediction-Climate Forecast System Reanalysis (NCEP-CFS Reanalysis 2013) sea surface pressure (hPa) and geopotential heights (gpm) at 500 hPa. More specifically, on February 13, 2004, a barometric low on the surface (1000 hPa) was established with its center over the eastern Turkey linked to a ridge (1030 hPa) towards Eastern Europe. This barometric turbulence resulted in northeast air flow in the region of eastern Greece and especially the Aegean Sea with near gale-to-gale winds (15–19 m/s) at 850 hPa level against severe gale winds (20–25 m/s) at 500 hPa level. As far as the middle atmosphere (500 hPa) is concerned, the existence of a trough over the Eastern Mediterranean had originated northern air flow towards Greece. These synoptic conditions caused advection of cold continental air masses towards Greece decreasing significantly the air temperature at the surface (2 m) from 0 to −10 °C.

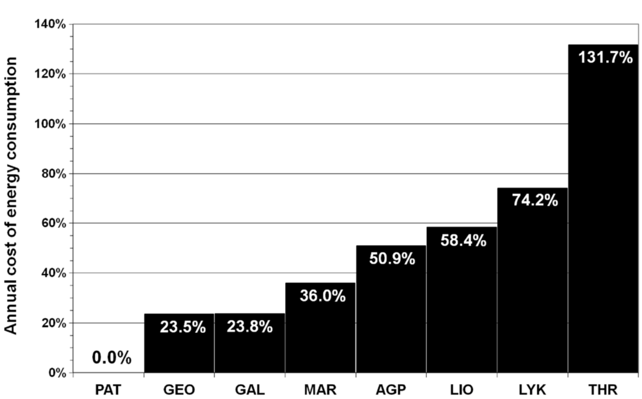

Fig. 7 Annual cost of energy consumption (%) for each one of the eight examined sites against PAT

Furthermore, the CDD maximum value outlier appeared on the same day (August 10, 2001) for the six of the eight examined areas. More specifically, on that day, CDD reached 7 °C day at LIO station (the absolute maximum value is 7.2 °C day within the period 2001–2005 at LIO station) and 3.4 °C day at THR station (the absolute maximum value is 5 °C day within the period 2001–2005 at THR station). This indicates that August 10, 2001 was the hottest day of the examined period 2001–2005 within GAA. Similar to the previous analysis on HDD, the results were verified by analyzing the synoptic conditions over the wider area of Greece on that day, based on NCEP-CFS Reanalysis (NCEP-CFS Reanalysis 2013) sea surface pressure (hPa) and geopotential heights (gpm) at 500 hPa. More specifically, on August 10, 2001, stable anticyclonic conditions appeared on the surface (1015 hPa) over the Eastern Mediterranean, resulting in moderate breeze winds (6–8 m/s) at 850 hPa level against light to gentle breeze winds (1–6 m/s) at 500 hPa level. As far as the middle atmosphere (500 hPa) is concerned, high geopotential heights were established over the wider area of Mediterranean and Eastern Europe resulting in the absence of significant weather disturbance. These synoptic conditions caused increased air temperature (30 °C) at the surface (2 m) over Greece.

Energy demand in Athens varies both in the intra-annual and inter-annual perspective. Under a changing climate, regional models predict warming for Athens by the twenty-first century that will be associated with a decrease in demand during the milder and shorter winter period and with an increase in demand during the hotter and longer summer period (Giannakopoulos and Psiloglou 2006).

5 Conclusion

In this study, a detailed estimation of HDD and CDD for eight different sites within the GAA is performed based on hourly air temperature data for a 5-year period (2001–2005). In accordance, the influence of urbanization on energy demand between neighboring locations within the GAA is examined, as well. For that purpose, a hypothetical specific residential building (a representative family house) is considered under the same conditions in the eight different monitoring sites within the GAA, in order the findings to be compared. Nevertheless, this could be a limitation because different types of buildings and their underlying weather sensitivities are very different from the downtown core to the more residential locations.

Results indicate a fairly significant difference for both HDD and CDD among the eight examined areas of the GAA. These differences between the center and the periphery of the city are important in a monthly and annual basis, as well. The annual number of CDD is almost sevenfold higher in the city center (Patission) than the peripheral area of the GAA (Thrakomakedones). In addition, the annual number of HDD at the peripheral areas within the GAA is about threefold higher than the number of HDD in the city center. The annual percentage of HDD is much higher than that of CDD in all examined sites. Taking into consideration the same hypothetical residential building in the eight different monitoring sites within the GAA, we found that the energy consumption for both heating and cooling within the GAA range from 8706 kWh (city center (PAT)) up to 20,049 kWh (north suburban site of THR). The same conclusions arise concerning the CO_2 emission in relation to the annual primary energy consumption at the eight examined regions within the GAA. A great variability of CO_2 emission appears within the GAA in relation to the type of energy consumed. Concretely, at the city center (PAT), about 40/60 % of CO_2 emission is due to heating/cooling against 90/10 % of CO_2 emission due to heating/cooling, in the suburban area of Thrakomakedones.

As far as the energy demand and energy consumption for cooling and heating buildings are concerned, using the HDD and CDD method, respectively, the differences between adjacent regions of a big city, like the city of Athens, Greece, should be seriously taken into account. Usually, the lack of hourly air temperature data for each individual district within a greater area results in using either data from a single specific district or mean composite data over the greater city area. The results of this study suggest that such an approach might lead to miscalculations and wrong judgments concerning the building's energy requirements. Besides, this study indicates that three different microclimate zones appear within the GAA. On this basis, engineers and building manufacturers should take into account all the previously mentioned differences between neighboring regions and the spatial distribution of HDD and CDD within the GAA, in order to avoid incorrect energy demands assessment resulting in the planning of nonenergy efficient buildings and constructions. Furthermore, research is needed, taking into consideration the specific types of buildings in the urban center against the suburbs, in order to assess better the implications of urbanization on energy consumption. A more detailed discussion of the factors affecting the building's energy consumption is needed in a future work, namely the shadowing from neighboring buildings, the wind and the radiation fluxes (solar receipt, longwave trapping), and urban design parameters such as width, height, and orientation, which modify the thermal conditions within street canyons.

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