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Estimating the characteristics of the Urban Heat Island Effect in Nicosia, Cyprus, using multiyear urban and rural climatic data and analysis

M.K. Theophilou[a,*], D. Serghides[b]

[a] Cyprus Department of Meteorology, Sector of Climatology and Applications in Meteorology, Cyprus
[b] Cyprus University of Technology, Department of Environmental Management, Cyprus

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ABSTRACT

In order to detect the Urban Heat Island Effect and its consequences on heating and cooling degree days, an analysis of the hourly meteorological measurements during the period 1983–2011 for the city of Nicosia in Cyprus has been conducted. The stations used were located in the City Center (station no.640) and the area of Athalassa (station no. 666) in Nicosia, which are low altitude Mediterranean climatic stations. The temperature change that has been identified on both stations has an impact on heating and cooling degree days. Cooling degree days follow a statistically positive trend for both stations. Heating degree days follow a negative trend for both stations, with the Nicosia City Center station being the only one with a statistically significant trend. Additional cooling degree days have been calculated for the station of Nicosia City Center during the summer period June–August, and less heating degree days during the winter period December–February, in comparison with the Athalassa Area Station, highlighting the existence of the Urban Heat Island Effect. The Urban Heat Island Effect is determined to be stronger during the winter period, mainly in February. Finally, the mean differences, as calculated, in cooling and heating degree days follow a non-statistically significant trend.

1. Introduction

The Urban Heat Island Effect deals with the increase of the ambient temperature in urban areas compared to the surrounding rural and suburban zones. Higher urban temperatures are the result of the positive thermal balance in the urban area caused by the characteristics of the urban layout, the materials used, the morphological, structural and physical features in the cities, the released anthropogenic heat, etc. [1]. The magnitude of the Urban Heat Island Effect depends on the above parameters as well as on the synoptic weather conditions in a place and the characteristics of the selected reference rural station [2].

Increased urban temperatures have a serious impact on the energy consumption of buildings during the summer period, affecting thus human health, deteriorate indoor and outdoor thermal comfort, raising the concentration of harmful pollutants and increasing the ecological footprint of the cities [3,4]. A significant number of published research studies show the increase of the cooling energy needs of the building sector because of the Urban Heat Island Effect [5–8]. According to Santamouris [9,10], five different types of energy studies have been proposed and performed, aiming to identify the energy impact of the Urban Heat Island Effect in individual buildings or in the whole building stock of a city. It has been shown that the energy penalty per unit of city surface caused by the Urban Heat Island Effect, varies between 1.1 and 5.5 kWh/m^2, while the Global Energy Penalty per person ranges between 104 and 405 kWh.

Urban Heat Island Effect is associated with higher concentrations of tropospheric ozone. The increase of the ambient temperature in cities acts as a catalyst and accelerates the photochemical reactions that form the tropospheric ozone [11]. Polluted days may increase by 10% for each 5 °F increase in ambient temperature [12]. Higher urban temperatures have a serious impact on human health and increase mortality rates in cities [13]. It is well accepted that the relation of the mortality rate and ambient temperature in a city follows a U shape curve, were mortality increases considerably over a threshold temperature [14]. This average threshold temperature for the Southern Europe cities is close to 29.4 °C [15].

The Urban Heat Island Effect affects seriously outdoor thermal comfort conditions. Several studies have shown that dense urban zones presenting a high anthropogenic heat release, suffer from

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* Corresponding author.
E-mail address: marios.theophilou@gmail.com (M.K. Theophilou).

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heat island and low outdoor comfort conditions [16]. Measurements performed in different parts of the world have confirmed the important relation between Urban Heat Island Effect and low outdoor thermal comfort levels [17–19]. In parallel, higher ambient temperatures affect seriously indoor environmental conditions in buildings since for the case of low income houses during the summer period over areas suffering from serious heat island intensity, most of the time indoor comfort conditions are completely out of the acceptable levels and put the health of the inhabitants in serious threat [20].

Mitigation of the Urban Heat Island Effect is a high priority for modern societies. Important techniques have been developed and have been applied in large scale projects with important and successful results [9,10]. Efficient design of mitigation and adaptation techniques in cities requires a full knowledge of the urban thermal characteristics. Actually, data on the specific Urban Heat Island Effect characteristics are available for hundreds of cities around the world [21]. Information is provided through different types of monitoring techniques involving data collected from standard and non-standard fixed meteorological stations and mobile traverses. The use of standard fixed meteorological stations provides an advantage: the measurements are available for long periods of time while the accuracy of the measurements is usually very high. On the contrary, the use of standard fixed meteorological stations does not provide specific information on the microclimatic thermal conditions of very dense urban zones.

The Urban Heat Island Effect in Nicosia has been studied by Theophilou and Serghides [22]. Based on the previous, the analysis of the mean yearly temperature for one rural and one urban station in Nicosia, shows that the mean yearly temperature for the rural and urban station has a positive statistically significant trend from the year 1998 onwards. Also, Neophytou et al. [23], have measured the heat island characteristics in Nicosia, during July 2010 using fixed and mobile stations and have concluded that during the night time, Nicosia is highly influenced by the katabatic winds from the surrounding mountains.

The use of heating and cooling degree hours as an indicator of the Urban Heat Island Effect characteristics in a place and its impact on energy is already proposed by many researchers [24–27]. Degree days are a means of evaluating the energy demand in order to maintain the indoor environment of a building in conditions of human thermal comfort [28].

This study analyses the temperature data of an urban and a rural station during the period 1983–2011, in order to identify the development and the characteristics of the Urban Heat Island Effect in Nicosia. The annual heating and cooling degree days are calculated and analyzed to evaluate the potential impact the local Urban Heat Island Effect has on the heating and cooling requirements of the buildings.

2. Data and methodology

An analysis of the meteorological measurements was conducted for a large time series (1983–2011) for the city of Nicosia, in order to determine the possible trends in local climate and identify the magnitude of the Urban Heat Island Effect. The hourly measurements used in this study have been recorder in two stations: Nicosia City Center and the area of Athalassa, as shown in Fig. 1. These areas are characterized by their low latitude and their Mediterranean climate i.e. a rainy season from November to February followed by a dry season March–October. The hourly measurements of temperature were extracted from the digitization process of the thermohydrograph and from automatic stations. The meteorological instruments are placed in a Thomas Stevenson box, 1.25 m above ground (approximately 4 ft) which is laid with short grass. The quality control of the data is ensured by the use of the quality standard ISO 9001:2008, and through the use of percentiles on the measurements, in order to check the amplitude of the values – Table 1. The trends for the datasets (slopes) are calculated using the least square method, while for the statistical significance of the trend, the Mann–Kendall trend test is used. The Mann–Kendall trend test calculates the t value of Kendall and in general it has an advantage over other tests because it also defines the period of time for which the trend becomes statistically significant [29]. The calculations regarding the significance of the trends from the Mann–Kendall test was conducted using the algorithm described in Livada and Asimakopoulos [29] book:

- Next to every x_i value, the k_i position is calculated (ascending position).
- For every x_i value, the number of cases n_i where the previous values are smaller than x_i are calculated.
- The t value of Kendall, standard deviation and standardized quantity $u(t)$ are calculated:

$$t = \Sigma(n_i)$$
$$t_{\text{mean}} = N * (N-1)/4$$
$$S_t = \text{sqrt}\,\{N * (N-1) * (2N+5)/72\}$$
$$u(t) = \text{abs}\,(t - t_{\text{mean}})/S_t$$

- The null hypothesis is H_0: $t = 0$ (no trend) versus the alternative hypothesis H_1: $t \neq 0$ (trend) are defined for confidence level of $\alpha = 0.05$ in a two tailed check.
- From the $u(t)$ value and through the normalized normal distribution $N(0,1)$ area table from 0 to Z, the probability α' is calculated and then α_1 value is calculated using:

$$\alpha_1 = 2 * (0.5 - \alpha')$$

- If $\alpha_1 > \alpha$, then the null hypothesis is accepted, while when $\alpha_1 < \alpha$ then the null hypothesis is rejected.

In order to calculate the period for which the trend becomes statistically significant, the algorithm below is used:

- For each and every value the consecutive sums t_i (of n_i values), the current mean t_i and the normalized current quantity $u(t_i)$ are calculated.
- In a two tailed check, the acceptance value for accepting the null hypothesis for $\alpha = 0.05$ is the $u(t) = \pm 1.96$, so the trend becomes statistically significant from the specific year and on when $u(t_i) > 1.96$. The sign shows if the trend is negative or positive.

For the cooling and heating degree days, the Spearman test of tendencies and the Mann–Kendall trend test are used. The Spearman test is also described in Levadas and Asimakopoulos book:

- Next to every x_i value, the k_i position is calculated (ascending position).
- The r_s correlation coefficient is calculated, using the formula:

$$r_s = 1 - 6 * \{(\Sigma k_i - i)^2 / N * (N^2 - 1)\}$$

It has been found that the r_s correlation coefficient follows the normal distribution with a mean value of zero and a standard deviation equals to $1/\text{sqrt}(N-1)$

- The null hypothesis is H_0: $r_s = 0$ (no trend) versus the alternative hypothesis H_1: $r_s \neq 0$ (trend) are defined for confidence level of $\alpha = 0.05$ in a two tailed check.