THE IMPACT OF SYNOPTIC-SCALE ATMOSPHERIC CIRCULATION ON THE URBAN HEAT ISLAND EFFECT OVER ATHENS, GREECE

G. Mihalakakou, H.A. Flocas and M. Santamouris

University of Athens, Dept. of Physics, Div. of Applied Physics, Lab. of Meteorology, University Campus, Build. Phys. V, 157 84 Athens, Greece.

ABSTRACT

The effect of the synoptic scale atmospheric circulation on the urban heat island phenomenon over Athens, Greece, was investigated and quantified for a period of two years, using a neural network approach. A neural network model was appropriately designed and tested for the estimation of the heat island intensity at twenty-three stations during the examined period. The day-by-day synoptic scale atmospheric circulation in the lower atmosphere for the same period was classified into eight statistically distinct categories. The neural network model used as an input the corresponding synoptic categories in conjunction with four meteorological parameters that are closely related to the urban heat island. It was found that the synoptic scale circulation is a predominant input parameter, affecting considerably the heat island intensity. Also, it was demonstrated that the high pressure ridge mostly favors the heat island phenomenon, while the categories being characterised by intense northerly component winds are responsible for its non-appearance or termination.

KEYWORDS

Neural Networks, Synoptic Scale Meteorology, Heat Island Phenomenon.

1. INTRODUCTION

The urban heat island (UHI) phenomenon is mainly caused by the differences in the thermal structure between urban and rural environment, being associated with thermal properties of urban materials, urban geometry, air pollution and the anthropogenic heat released by urban activities (Park, 1986). The phenomenon may occur during day or nighttime period while its spatial and temporal pattern is strongly controlled by the unique characteristics of each urban area. The heat island intensity can be quantified by the maximum difference between urban temperature and the background rural one and depends on the size, population and industrial development of the city, topography, physical layout, regional climate and meteorological conditions (Oke et al. 1987).

The effect of meteorological parameters on UHI magnitude was the subject of considerable research. These studies revealed that wind speed and cloud amount are the most important parameters that influence the development and intensity of the UHI, suggesting that UHI intensifies under cloudless sky and light wind conditions. However, only few studies have been dealt in depth with the effect of the prevailing synoptic scale weather conditions on the UHI phenomenon (Unger, 1996).

The city of Athens is characterized by a strong heat island effect, mainly caused by the accelerated industrialization and urbanization during last years. The effect appears during both summer and winter periods, with mean daily intensity ranging between 6-12C for the major central area (Santamouris et al. 1999).

Neural networks are computational systems that simulate in a simpler way the structure and functions of the human brain (Li et al. 1990) and, therefore, are considered capable to model complex nonlinear processes. They belong to the class of "data-driven" approaches instead of "model-driven" methods because the analysis and the results depend on the available data (Chakraborty et al. 1992). Relationships between variables, models, laws and predictions are constructed after building a machine which simulates the considered data. The process of constructing such a machine based on available data is addressed by certain algorithms like "perceptron" or "backpropagation".

The present paper aims at investigating the influence of the synoptic scale circulation in the lower troposphere on the UHI in the Greater Athens Area (GAA) on a daily basis, utilizing a neural network approach. This approach allows the quantification of the relationship between synoptic scale circulation and UHI magnitude as well as the assessment of the UHI under different synoptic conditions.

2. THE URBAN HEAT ISLAND EXPERIMENT IN ATHENS

The GAA is situated in a small peninsula located in the southeastern edge of the Greek mainland. The urban heat island phenomenon in GAA was examined using hourly measurements of ambient air temperature and humidity from twenty-three experimental stations, being installed in the Athens urban and suburban region, for a period of two years, 1997 and 1998. A brief description of each experimental station is presented in Table 1. Seven stations were placed in the central area of Athens, fifteen stations were placed in urban areas and in a radial configuration around Athens centre. Station 2 was situated in the slope of Hymettus mountain (at an altitude of about 500 m), in an almost rural, non built-up region with moderate vegetation and no traffic. The climate of GAA is typical "Mediterranean", with mild winter and dry hot summer.

TABLE 1
Characteristics of the experimental Stations

Station Number	Station Characteristics
1	Placed on a green hill at the centre of Athens (altitude=107m). The area is characterised by low building density and absence of traffic.
2	Placed in the south-eastern area of Athens near a mountain. The area is less populated with low traffic and medium building density.
3	Placed in the eastern area of Athens centre. The area is densely populated with a lot of

	traffic
4	Placed in the south-western area of Athens. The area is less populated with low traffic while its vegetation is nearly negligible
5	Placed in the eastern area of Athens near a mountain. The area is highly populated with a lot of traffic
6	Placed in the southern coastal area of Athens, very close to the airport. The area is characterised by very low traffic and by very few buildings
7	Placed in the centre of Athens. The area is densely populated with heavy traffic
8	Placed in the north-eastern area of Athens between two mountains. The area is characterised by an increased building's density and by heavy traffic
9	Placed in the southern area of Athens centre in a big avenue. The area is highly populated with heavy traffic
10	Placed in the southern side of the previous avenue very close to the sea. The area is characterised by low building's density and by heavy traffic
11	Placed in the centre of Athens in a pedestrian road. The area is very densely built and populated
12	Placed in the centre of Athens. The area is characterised by a lot of traffic and by very dense population
13	Placed in the centre of Athens. Traffic and buildings' density are very high
14	Placed in the western area of Athens in a university campus characterised by a moderate vegetation
15	Placed in the centre of Athens. The area is very densely populated with a lot of traffic
16	Placed in the northern area of Athens. Traffic is very low and trees are scattered all over the area
17	Placed in the western limits of Athens basin in a foot-ball ground at the edge of a planted area. The area is characterised by very low traffic and buildings' density
18	Placed in the western area of Athens. Traffic is heavy while buildings' density is very high
19	Placed in the city centre inside National Garden of Athens
20	Placed in the Ancient Market of Athens. It is an area covered by bare soil and surrounded by trees
21	Placed in the north-eastern area of Athens in a suburb with increased traffic and average vegetation
22	Placed in the centre of Athens. The area is characterised by heavy traffic and large green spaces which consist of gardens and trees
23	Placed very near the centre of Athens in a big avenue. The area is not very densely built with an average street vegetation but its traffic is high

3. THE NEURAL NETWORK ARCHITECTURE

The estimation or prediction problem using neural network models can be separated into three steps or sub-problems: designing the neural network architecture, learning or training process and testing or diagnostic checking. In the present study a multiple layered neural network architecture, based on backpropagation algorithm, was selected for the estimation of the urban heat island intensity at each experimental site. An error goal of 0.5 was selected and the number of epochs varied between 2000 and 3000. The main source of error seems to be the site-specific topographic conditions of some stations that cannot be perfectly described by the input parameters.

The input parameters of the neural models were the following:

a. *Synoptic scale atmospheric circulation*

The 850 hPa atmospheric circulation was classified into eight a priori determined categories on a daily basis for two years period (1997-1998), for all seasons, according to the form and relative position of the synoptic scale features, that typically represent the complete range of the atmospheric circulation over the Mediterranean basin. The occurrence of the heat island phenomenon is then assessed relative to the synoptic categories (circulation-to-environment approach). This manual classification scheme was proposed and employed by Kassomenos et al. (1998) for the GAA for a period of 16 years (1980-1995). The synoptic categories are as follows:

1. LONG-WAVE TROUGH
2. SOUTH-WESTERLY FLOW
3. NORTH-WESTERLY FLOW
4. ZONAL FLOW
5. CLOSED LOW
6. HIGH PRESSURE RIDGE
7. CLOSED ANTICYCLONE
8. CATEGORY HIGH-LOW

b. *Ambient air temperature measured at each station*

This parameter is measured at each station when the maximum heat island intensity is observed. Usually, the air temperature in the urban environment is significantly higher than the corresponding rural temperature.

c. *Ambient air temperature measured at the reference station*

This input parameter is measured at the reference station when the maximum heat island intensity is observed.

d. *Maximum daily values of total solar radiation*

Short-wave radiation is an important factor for the urban heat island estimation as it represents the amount of energy, which arrives at the ground surface as direct and diffused radiation.

e. *Mean daily values of wind speed*

Calm or low wind conditions are found to be conducive for strengthening of the urban heat island, while increases in the wind speed restrict the development of the phenomenon. In this study, the wind speed was inserted in the model in the form of mean daily values being measured at station 1.

4. RESULTS AND DISCUSSION

a. Modeling the Urban Heat Island Intensity

Training was performed using the input parameter values for the estimation of the heat island intensity for 500 days of 1997 and 1998. The training results were compared with the measured ones for each station and the comparison showed that the estimated heat island intensity values perform well with the measured ones for the whole set of experimental stations. The correlation coefficients fluctuated between 0.90 and 0.97 while the root mean square errors varied in the range of 0.1C to 0.4C.

Similar results were achieved for the whole set of the twenty-two stations. The correlation coefficients varied between 0.85 and 0.97, while the root mean square errors varied from 0.1C to 0.6C. In order to test the results of the neural network, the model estimations were compared with the corresponding measurements of UHI intensity for the remaining 230 days of 1998 that consist the testing data set. High values of the UHI intensity are achieved for all stations and especially for station 12, that is regarded as the most representative of strong urban conditions as is characterized mainly by heavy traffic, increased air pollution and high buildings' density. A good agreement is observed between the estimated and measured data for the whole set of testing data. The 90% of the relative error values range between -10% and 14%. The correlation coefficients between measured and estimated values vary from 0.86 to 0.94 while the root mean square errors range between 0.1C and 0.3C.

b. Influence of Synoptic circulation on the Heat Island Intensity

The influence of each synoptic category was examined on the basis of the correlation coefficient between the measured and the estimated values of the UHI intensity. It was found that the synoptic category being associated with the highest correlation coefficient (for 85% of the UHI days) is 6, implying that this category mainly favors the development of UHI phenomenon. This is because this category is characterized by weak flow regime, while it is the most frequent during the warm period (May-September) as compared to the other categories with relative frequency of appearance during the examined period of 43%. The other anticyclonic category 7 seems also to have an impact on the UHI phenomenon but considerably smaller, due to the very limited frequency of appearance (0.8%) during the warm period. On the contrary, categories 3 and 8 do not improve significantly the correlation coefficient between the measured and simulated UHI intensity values and, therefore, seem to be responsible for the absence or termination of the phenomenon. This is caused by the strong winds that occur during the predominance of the above mentioned categories. In order to investigate the influence of atmospheric circulation on the estimation of the urban UHI intensity, neural network models were designed and trained using only the atmospheric circulation as input parameter, for twelve randomly selected experimental station and for the same time period. Table 2 shows the correlation coefficients and the root mean square errors between measured and estimated UHI intensity values when: a) all five previously presented parameters were used as inputs to the neural models, (1, RMSE1) and b) atmospheric circulation was the only input parameter, (2, RMSE2). Moreover, Table 2 displays the (%) reduction of the correlation coefficient _1 and _2. It was demonstrated that the synoptic conditions as the only input parameter contribute significantly to the UHI intensity estimation with correlation coefficients reaching 0.77. The corresponding RMSE ranges between 0.25 and 0.38 in the majority of the stations while presents higher values in stations 6, 9 and 19. The correlation coefficient reduction between measured and estimated values varies between 18.1% and 26.4%. Therefore, it seems that the atmospheric circulation affects considerably the UHI intensity, since it is responsible for the formation and evolution of the meteorological elements, which can enforce or eliminate the phenomenon. Similar results were also achieved for the whole set of the twenty-three stations.

TABLE 2
Correlation coefficients (_) and root mean square errors (RMSE) between the measured and neural networks estimated heat island intensity values when all parameters are used as inputs (1, RMSE1), and atmospheric circulation is the only input parameter, (2, RMSE2).

Station number	λ_1	λ_2	$RMSE_1$	$RMSE_2$	(%) Reduction
1	0.91	0.67	0.36	0.46	26.4
3	0.88	0.72	0.54	0.62	18.2
6	0.90	0.70	0.44	0.55	22.2
9	0.87	0.69	0.53	0.64	20.7
10	0.92	0.74	0.33	0.38	19.6
12	0.94	0.77	0.26	0.31	18.1
13	0.93	0.73	0.29	0.35	21.5
14	0.92	0.72	0.35	0.42	21.7
15	0.90	0.69	0.38	0.48	23.3
18	0.91	0.68	0.35	0.44	25.3
19	0.88	0.66	0.53	0.65	25.0
20	0.94	0.71	0.25	0.32	24.5

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