Indications of the Urban Heat Island in Athens, Greece

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(Manuscript received 24 September 1984, in final form 3 May 1985)

ABSTRACT

The analysis of air temperature data for a period of 22 years in the meteorological network stations in the greater Athens area shows clearly the effect of the urban heat island due to the city. This effect appears with different intensity according to the season and to minimum and maximum temperatures. In particular, the analysis of the data pointed out the variations caused by natural processes and anthropogenic activities. The influence of the growth of the city on the mean minimum temperature is evident.

1. Introduction

The Athens basin (φ = 37°58'N, λ = 23°43'E), presents the urban climatologist with an extremely complex situation. Under given synoptic conditions there are three interacting sets of climatic controls, each operating on different space and time scales. These controls are topography, urban morphology and proximity to the sea. Consequently, the Athens greater area presents some difficulties for estimating the urban heat island because of the effect on temperatures of 1) the adjacent sea, 2) major changes in elevation, and 3) the local circulations that can occur because of the urban morphology and the complex terrain. For the purpose of this study, in the following we will outline the main features of these controls.

There is a growing interest in studies on climate and its modifications for the purpose of developing models for forecasting the climatic evolution of the earth. The examination of climatological modifications produced by man has become in recent years very important for the study of climatological trends on a planetary and local scale. The analysis of a long series of air temperature data provides important information of use in attaining these two interrelated objectives, since variations of this parameter are considered indicative of any climatic modifications (Metaxas and Vassiliou, 1978). This work is an analysis of the air temperature for the period 1961–1982 in the network stations of Athens basin. The stations are representative of the urban and rural conditions, so useful indications can be implied on the mean characteristics of Athens heat island. The results are presented and discussed and some estimations of the difference between urban and rural temperature ΔT_{u-r} are carried out on the basis of relationships found in literature, e.g., Oke (1974, 1979), Landsberg (1981) etc. The values obtained seem to be in good agreement with those attained by analysis of the temperature data.

2. Description of the area and the network

The network stations in the greater Athens area used for the present work are shown in Fig. 1. The area, with its particularities, presents characteristics which make it especially interesting for such studies. Athens basin with an estimated population of 3.2 million in 1981 covers approximately a 450 km^2 area with fairly high mountains on three sides (Aigaleo to the west, Parnitha and Penteli to the north, Hymettos to the east) and the sea on the fourth; the basin is bisected by a series of small hills. The climate of Athens is Mediterranean in character (Eginitis, 1907).

The climatological stations considered (Table 1) are representative of the different areas present in this district: coastline, rural, suburban and urban. The period examined from 1961–82 corresponds to the period of maximum development of the city and so it is particularly suitable to check the validity of some formulae between temperature variations and urban development. The Meteorological Station of the National Observatory of Athens, which is situated at 107 m msl and 45 m above the level of the city is the basic station with a period of measurements from 1860 to 1982 (123 years).

3. Data analysis: Results of the analysis of data from the network stations

The measurements of air temperature are carried out three times a day: 0800, 1400 and 2000 and min-

TABLE 1. List of stations used.

Station number	Height (m)	Type
1. Athens (Kotjia square)	74	Urban
2. National Observatory	107	Urban on a hill
3. Nea Philadelphia	138	Suburban
4. Helliniko (Airport)	10	Suburban next to the sea
5. Anavrita	290	Suburban on the north hills
6. Tatoi	238	Rural
7. Elefsina	30	Suburban, next to the sea
8. Pireas	2	Urban coastal
9. Peania	152	Rural

imum and maximum temperatures are also recorded. With these five values the mean diurnal temperature is determined from which the monthly ones were obtained for use in the present work. For each mean value the standard deviation was also calculated in order to verify the data according to the ordinary criteria of the statistical distributions, e.g., the t-distribution tables with $n - 1$ degrees of freedom (since the standard deviation is obtained from $n < 30$). Figure 2 shows the monthly data patterns recorded in the different stations for the minimum, mean and maximum temperatures. The curves of the minimum mean temperatures show that the minimum values occur in January, ranging from 3°C in the Anavrita suburban station to 7.8°C in the coastal station of Pireas. In the city the temperature is about 6.5°C, whereas in the rural areas it is about 3.5°C. For the mean temperature: the lowest values occur also in January ranging from 7.5°C at Anavrita suburban station to 10.8°C at Pireas. Within the city the minimum values of mean temperature are about 9°C. The mean maximum values occur during July and August, ranging from 31°C in Pireas to 33°C in Nea Philadelphia and Elefsina. In Athens a value of about 33°C is recorded.

Furthermore, the curves show strong temperature changes occurring during the transitional seasons, whereas in winter and in summer these changes are

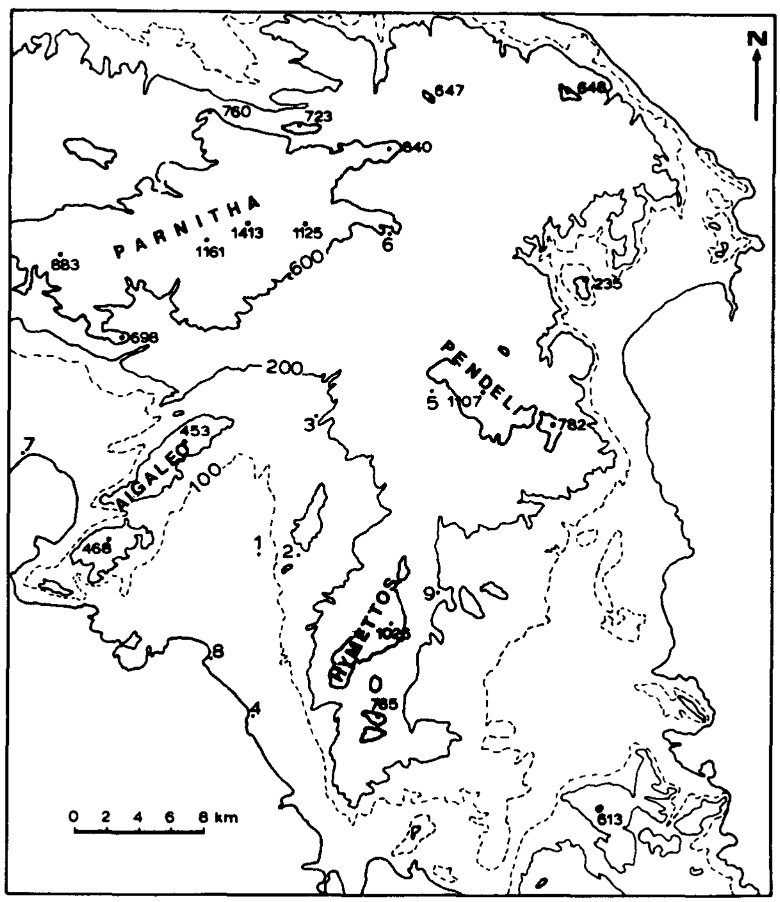

FIG. 1. Map of the Athens area showing the stations network: 1) Kotjia Square (Athens Center), 2) National Observatory, 3) Nea Philadelphia, 4) Helliniko (Airport), 5) Anavrita, 6) Tatoi, 7) Elefsina, 8) Pireas, 9) Peania. Elevation in metres.

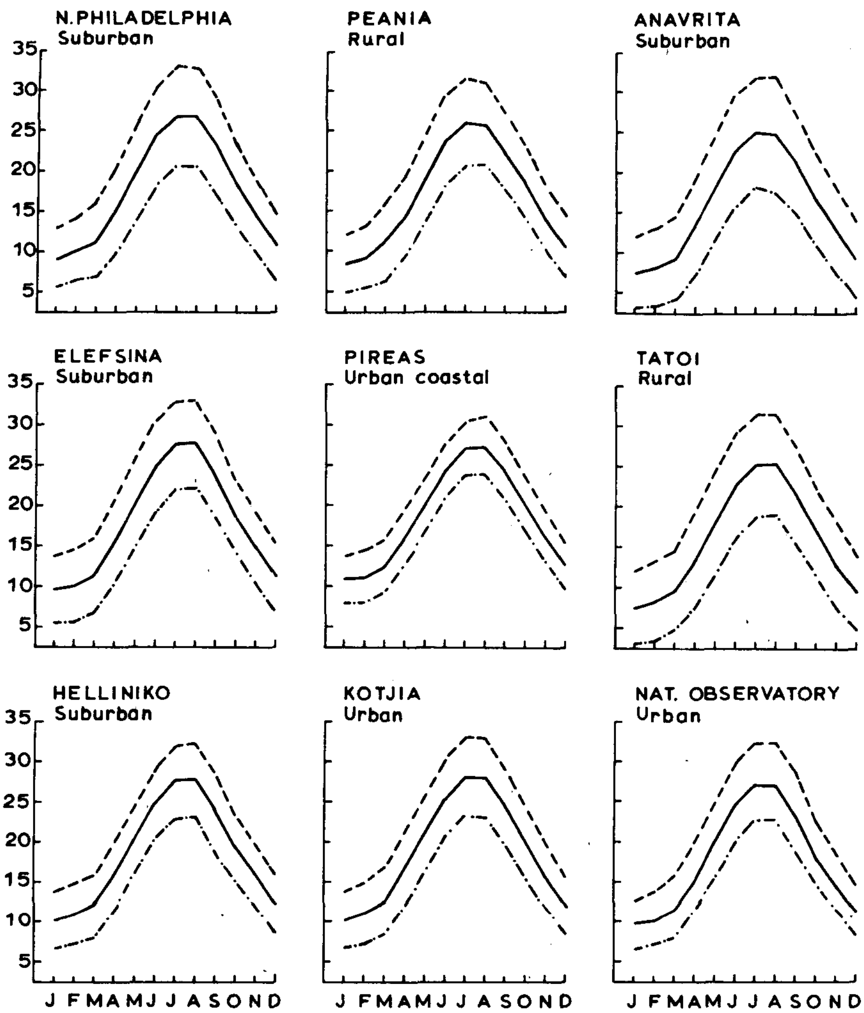

FIG. 2. Mean monthly temperatures (°C) (min, mean and max) for the network stations.

reduced. It is possible to deduce from the data that very small changes occurring during December–March will increase in the following months, reaching the maximum in April and May. Then the rate of temperature change will decrease reaching the minimum between July and August and again will increase with a maximum between September and October.

In Table 2, the diurnal temperature ranges of the mean temperature are given. They show clearly that they depend on the coast distance: in Pireas such variation is approximately 6–7°C with an annual variation of about 1.5°C. After this station we have Helliniko Airport with an annual variation of about 2°C. The inland stations however present a variation of about

TABLE 2. Mean monthly values of the diurnal temperature range ΔT (°C).

Station	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec	Year
1	7.2	7.7	8.3	9.4	9.7	9.5	9.6	9.7	9.5	8.9	7.9	7.3	8.7
2	6.2	6.8	7.5	8.6	9.0	9.6	9.7	9.7	9.5	7.8	7.0	6.3	8.1
3	7.2	7.6	9.1	10.6	11.8	12.5	12.4	12.1	11.6	9.9	8.5	7.9	10.1
4	7.2	7.8	7.7	8.4	8.3	8.4	9.3	9.4	9.0	8.1	7.6	7.0	8.2
5	9.0	9.8	12.0	12.0	13.0	13.9	13.7	13.4	12.4	11.0	10.7	9.2	11.7
6	8.9	9.6	9.7	11.8	13.1	13.2	12.7	12.4	12.0	10.8	10.3	9.0	11.1
7	8.0	8.9	8.9	10.1	10.8	11.2	10.8	10.9	10.1	8.9	9.0	8.2	9.7
8	5.8	6.3	6.5	6.8	6.6	6.9	7.2	7.3	7.3	6.9	6.4	5.9	6.7
9	7.0	7.6	9.7	9.7	10.6	11.2	10.9	10.2	9.7	9.0	8.0	7.5	9.3

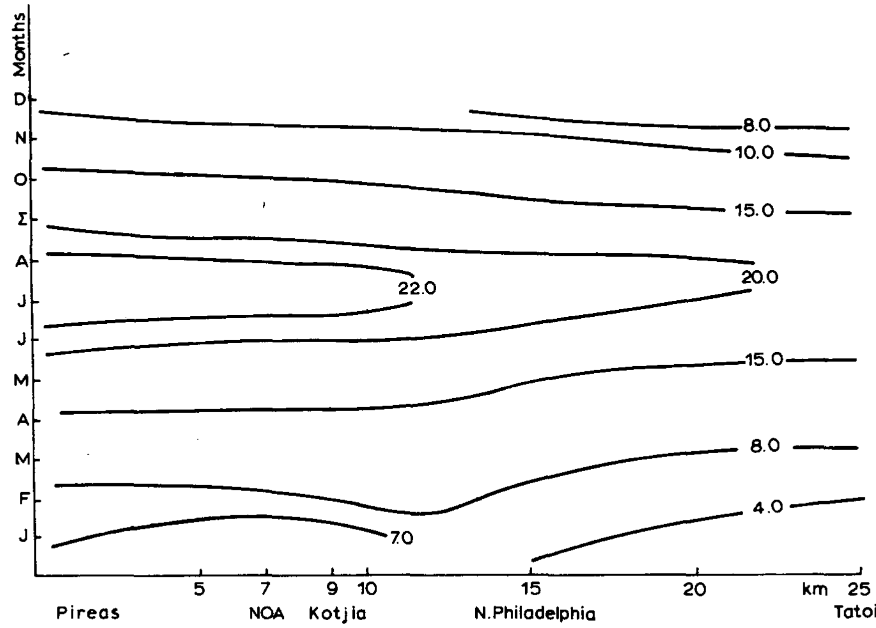

FIG. 3. Time–space section of the mean minimum temperature (°C) perpendicular to the coastline.

5°C, except for the urban stations in which the minimum temperature values, mitigated by the effect of the heat produced by human activities, cause an annual excursion of 3–4°C.

Examining the possible effect of station elevation on the diurnal temperature range, it may be said that no significant influences of the elevation of stations on the daily temperature range seem to exist. The conversion of the values of the temperature range in Table 2 down to sea level showed that the reductions to the monthly values of the daily temperature range are less than 1°C, except of the Anavrita station (5) where the mean annual value of the temperature range is reduced to about 1.5°C.

4. Urban heat island

In order to determine the effect of the urban heat island relative to the surrounding areas, a spatial-temporal section was carried out with the mean values of the minimum temperatures collected in stations located at progressively increasing distances from the coast. The section gives month by month trends of the minimum temperature from the coast through the city up to the rural station at Tatoi and is represented in Fig. 3.

Taking into consideration these minimum temperatures the presence of the heat island appears clearly either during the winter months or during the summer months with increasing values from the winter towards the summer.

Comparing the Athens (Kotja Square) urban station (*u*) and the Tatoi rural station (*r*) (with 154 m elevation difference), the two rural stations of Tatoi and Peania (with 86 m elevation difference), the two noncoastal suburban stations (*s*) of Nea Philadelphia and Anavrita (with 152 m elevation difference), and again the Athens urban station and Peania rural station (with 78 m elevation difference), we obtain for the ΔT_{u-r}, ΔT_{r-r}, ΔT_{s-s}, and ΔT_{u-r} differences during the year the trends given in Table 3, respectively. It can be seen that the effect of elevation is to increase the temperature contrasts. In a general sense, it is obvious that the city generates a heat island, with temperatures increasing from the suburbs to the center. Due to the topographic (changes in elevation) and other complicating factors

TABLE 3. Minimum mean monthly temperature differences of city and surroundings (°C).

Temperature difference	Month												Year
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec	
ΔT_{u-r}	3.3	3.1	2.9	3.8	4.1	3.9	3.9	3.6	3.7	3.7	3.9	3.3	3.6
ΔT_{r-r}	1.9	1.9	1.5	2.0	2.2	2.2	1.8	1.6	2.0	2.5	2.2	1.9	2.0
ΔT_{s-s}	2.5	3.3	2.5	2.6	2.1	2.2	2.4	2.0	2.0	2.0	2.2	2.0	2.3
ΔT_{u-r}	1.7	1.8	2.1	2.6	2.4	2.5	2.7	2.5	2.2	1.4	2.0	1.6	2.1

TABLE 4. Minimum mean temperature difference for urban (u)–suburban (s) coastal stations (ΔT_{u-s}, °C).

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec	Year
ΔT_{u-s}	2.3	2.4	2.3	2.2	1.9	1.6	1.6	1.6	2.0	2.6	2.8	2.7	2.1

it is hard to place a definite value on the magnitude of the heat island, but it seems reasonable to suggest a figure of at least 2–3°C.

Examination of the mean and maximum temperatures, however, indicates that the effect of the urban heat island becomes less evident and tends to disappear. With the mean and maximum temperatures the effect, which is deduced from the data, is essentially connected with the presence of the sea. In fact, during the winter months the temperature along the coastal area is higher and slowly decreases inland. Additionally, along the coastal area, the heating from the solar radiation is moderated by the presence of the sea and therefore in summer along the coast the values are lower than those of the inland areas. Therefore, a gradient of opposite sign to that appeared in winter is recorded and practically the effect of the sea presence is felt up to a distance of about 15 km from the coast. Beyond this distance there is a uniform temperature pattern which tends to increase going towards the inland. The heat island effect was also indicated by the data analysis of the stations aligned parallel to the coast, especially in the minimum temperature (see Table 4).

The presence of the heat island, more in the minimum temperatures than in the mean and maximum ones, may be explained by the physical mechanisms which define the effect, e.g., the heat production from anthropogenic activity, and the heat release during the night due to the greater diurnal absorption of solar radiation, which depends on the thermal characteristics of the buildings (Oke, 1979).

Referring to the first mechanism of the heat production, an evaluation relative to the winter months and based on the fuel consumption for human activities (heating, traffic etc.) indicates a heat production about 10 W m^{-2} d^{-1} (Interim Technical Report, 1975). Data averaged over a 25-yr period give for the insolation (average global solar radiation on a horizontal surface) in Athens in the winter time a value of about 90 W m^{-2} d^{-1}, which corresponds to 80 W m^{-2} d^{-1} received by the city. It can be seen then that the anthropogenic heat production is an important factor in the increase of the minimum temperatures during the winter because, being due to the building heating, it is generally produced during the hours after sunset.

As far as the heat release is concerned, it is particularly important to explain the increase of the summer minimum temperatures (Colacino and Lavagnini, 1982). In this regard, from the calculations carried out in this analysis, it is concluded, in fact, that the maximum temperature difference is observed in the nighttime hours and this confirms what was also found by others (e.g., Oke, 1979).

Regarding the feasibility to express ΔT_{u-r}, different formulae were proposed which relate the ΔT_{u-r} values either with meteorological parameters, such as the wind, or the temperature gradient recorded in rural districts, or with parameters which express the size of the city, such as the population.

For cities with over 2 000 000 in population, Ludwig and Kealhoa (1968) suggest the relationship

$$\Delta T_{u-r} = 2.6 - 14.8\left(\frac{\Delta\theta}{\Delta p}\right)_r,$$

where $\Delta\theta/\Delta p$ is the vertical lapse rate observed in the rural area. This relation was modified by introducing the population P (Ludwig, 1970),

$$\Delta T_{u-r} = P^{1/4}\left[0.633 - 0.298\left(\frac{\Delta\theta}{\Delta p}\right)_r\right].$$

Also, Oke (1974) proposed in clear sky conditions for the maximum value ΔT_{u-r} the relationship

$$\Delta T_{u-r} = \frac{P^{1/4}}{4\bar{u}^{1/2}},$$

with $\bar{u}$ the mean wind velocity.

By using the data available for the rural station (Peania) for the difference ΔT_{u-r} the values presented in Table 5 are derived.

It may be seen from the above data, that the different relations suggested give somewhat underestimated re-

TABLE 5. Computed and observed values at ΔT_{u-r} (°C).

	Computed			
	Ludwig and Kealhoa	Ludwig	Oke	Observed
Winter	2.0	1.6	—	3.2
Summer	2.3	2.4	—	3.8
Year	2.2	2.0	3.5	3.6

TABLE 6. Temperature–population parameters.

Correlation	a	b
$T_{min} - \sqrt[4]{P}$	8.146 ± 0.154	0.030 ± 0.009

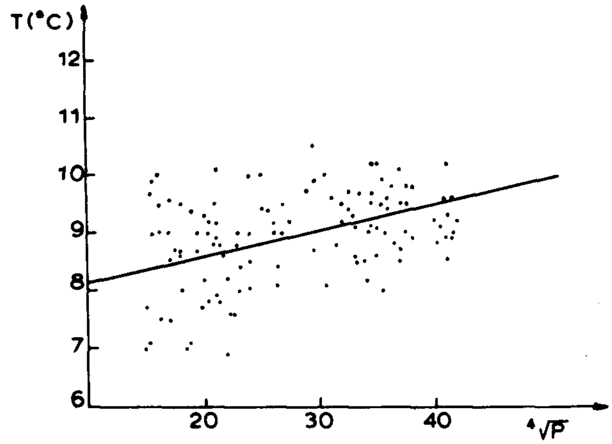

FIG. 4. Scatter diagram obtained for the correlation between temperature sequence and population number following the fourth root relationship.

sults in comparison with the values ΔT_{u-r} experimentally obtained. A considerable difference also is found when considering the correlation proposed by Oke (1979) with data for some European cities. But the Oke relationship was developed from the largest urban-rural differences measured during study periods of limited length. In many cases they were maxima in the spatial patterns determined from automobile traverses. These measurements represent the extremes in the distribution, whereas averages based on climatological records represent a central value. Consequently, this may partly be explained by the fact that Athens is subjected to high wind speeds; e.g., the mean wind speed is approximately 3–4 m s^{-1}, especially in winter and summer months. So it can be thought that the wind action, even if not entirely covering up the effect of the urban heat island, causes a reduction of ΔT_{u-r} differences with respect to those that could be observed in the case of calm conditions.

On the other hand, the differences in the maximum and minimum temperature trends that are discussed in Section 5 may be interpreted as a long-term variation due to the city's growth and the result of increasing urban temperature due to human causes. This effect is more apparent in the minimum temperatures than in the maximum ones, since the urban heat island effect is more noticeable during the night than during the day (Oke, 1974; Landsberg, 1981; Colacino and Lavagnini, 1982). Minimum urban temperature increase is usually explained by linking the temperatures with the resident population, a parameter that reflects the size of the city itself. For Athens, the statistical correlation analysis was carried out using annual data referring to the resident population from 1861 until 1982, together with the corresponding minimum temperatures. Regression was carried out using the relation (Colacino and Rovelli, 1983).

$$T_{\min} = a + b\sqrt[4]{p}. \quad (1)$$

Table 6 shows the data referring to the linear regression of Fig. 4.

This value is in agreement with the mean minimum values, i.e., 8.0–8.5°C, found in the rural areas around Athens.

5. Air temperature trends

The annually averaged air temperatures for the National Observatory (mean, minimum, maximum) are given in Fig. 5. The values were obtained from the mean daily temperatures. The diagrams show the trends of these mean values. The mean annual air temperature is $\bar{T}$; the mean annual minimum and maxi-

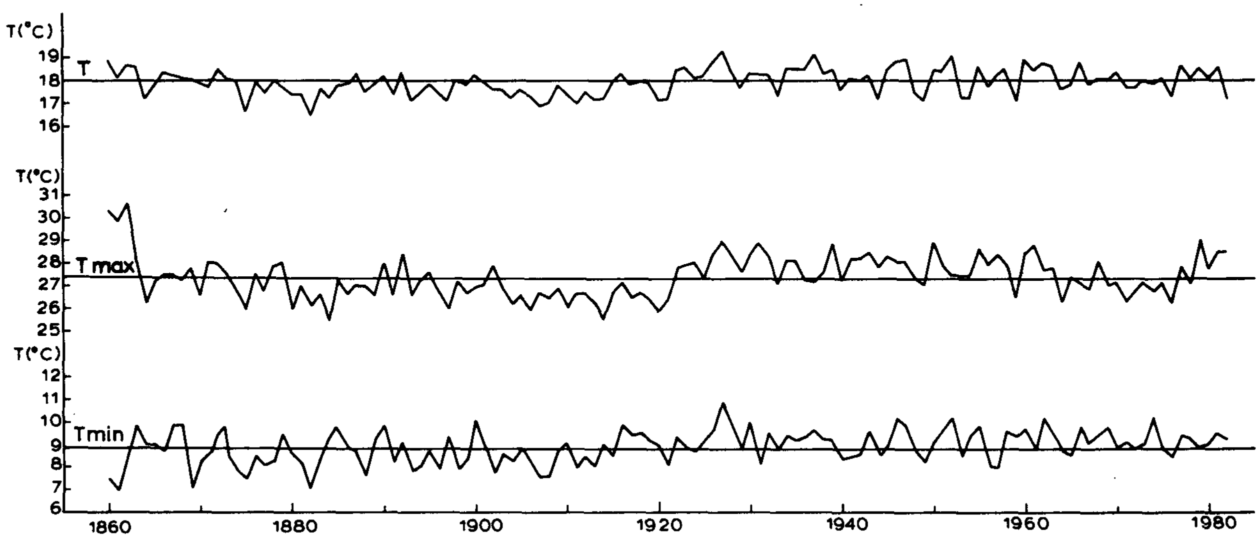

FIG. 5. Mean annual values of the air temperature in Athens (1860–1982).

TABLE 7. Temperature data for Athens.

Period	T_m (°C)	$\bar{T}$ (°C)	T_M (°C)
1860–1890	8.23	17.85	27.41
1891–1920	8.65	17.58	26.73
1921–1950	9.16	18.23	27.94
1951–1980	9.21	18.11	27.14
1958–1982	9.27	18.10	27.43
1860–1982	8.92	17.94	27.35

mum temperatures are $T_{\min}$ and $T_{\max}$, respectively. The recordings start in 1860. The mean annual temperature for the whole period is 17.98°C. During 1874–1915 the annual means were under this value. After that, they tend to increase and the temperature remains above or fluctuates around the mean value. A tendency towards decreasing temperature is found after 1961. The distribution of the mean maximum temperatures shows a similar trend to that of the mean temperatures. The mean value for the whole record is 27.3°C. In the period 1860–1902 the values fluctuate around the mean. In subsequent years, up to 1922, the values are less than the mean. During 1923–64 the mean maximum temperatures are higher than the average, and show a decrease in recent years. The minimum temperatures show a different pattern. During the period 1860–1922 the values are fluctuating around the mean (8.8°C), or are lower than this value. Between 1922 and 1982 there is little trend obvious in the minimum temperatures; they are consistently above the long-term means. This is probably due to the growth of the city.

From these long-term series one can also conclude that, in the 1960–82 period, not only did the minimum temperatures tend to be above their long term average but maximum temperatures tended to be below theirs, resulting in mean temperatures close to the long-term mean; mean diurnal temperature ranges tend to be larger. These deductions from the urban temperature series are in agreement with the evidence presented earlier from the network analysis.

Finally, the heat island effect may be said to partially explain the increase in minimum temperature as a long-term variation affecting the local microclimate.

We conclude by saying that the presence of the urban heat island effect on the minimum temperatures is also confirmed by comparing a previous data series showing very clearly the minimum temperature increase. This increase is particularly significant for the recent years in which instead, a temperature decrease is observed in the mean and maximum values. The data with which the comparison is made are presented in Table 7 and were taken for 30-yr periods, starting from 1860. The first examination clearly shows that while the mean and maximum temperatures show an increase in the years 1891–1950 and a subsequent slight decrease during recent years, the minimum temperatures show a tendency to increase, also in the period 1951–80. In the same period the population of the Athens basin increased from 1 430 000 (1951) to 3 200 000 (1981).

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