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Statistical and persistence analysis of high summer ambient temperatures in Athens for cooling purposes

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Abstract

The increase of living standards in buildings and the recent high summer temperature values have dramatically increased the installation of cooling systems in buildings. Analysis of the summer ambient temperatures is thus necessary in order to provide appropriate information to designers and to investigate possible increasing trends of ambient temperature having an important impact on energy consumption.

A statistical analysis of the summer ambient temperature data is presented in order to provide information for evaluation of passive, hybrid and conventional cooling systems and techniques. Multiyear data of Athens, Greece, have been used. No statistically significant increasing or decreasing trend of the hot and very hot summer hours was found.

The persistence of high summer temperatures was also calculated and found to be statistically significant. Probabilities of hourly temperatures being higher than a temperature base are calculated for each month.

1. Introduction

Avoidance of overheating during the warm period is a major concern in hot climate countries. Thermal comfort in indoor spaces can be achieved using appropriate architectural design principles, together with heat removal techniques, and auxiliary cooling equipment.

An increase in living standards has promoted the use of conventional air-conditioning (AC) systems. An increase of 300% in the total market has been registered for the period 1976–1985 presenting today a market turnover of U.S.$ 20 billion [1]. This increase is extremely important for selective countries like Greece where the purchase of air conditioners during the last three years has increased by 800% approximately. [2]. The impact of air conditioners on the peak electricity load is extremely important. Thirty eight percent of the non-coincident peak demand in the U.S.A. is induced by air-conditioning [3]. Therefore reduction of the AC-induced load is a major concern for utilities and energy experts.

Various research and development policies are defined and proposed, in order to reduce the impact of air conditioners [4]. Tasks of primary importance are the development of methods for appropriate sizing of AC systems and the use of passive and hybrid cooling techniques like ventilative, evaporative, radiative and ground cooling. Errors of about 200% in calculated cooling loads are reported, leading to oversizing of the AC systems [5]. Correct calculation of the cooling load of buildings, appropriate sizing of AC systems and integration of passive and hybrid cooling techniques and components within the building are directly related to the availability of local climatic data, of which ambient temperature is the most important.

The basic parameters and the information related to ambient temperature, necessary for the design of cooling systems are described in ref. 6. However, research on passive and hybrid cooling systems and techniques demands a more profound and extensive analysis of the ambient temperature data involving so-

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phisticated analysis of its reported variation. These data are absolutely necessary for the design of convective cooling and the evaluation of the ventilation capability in a place. They are also necessary for the evaluation of buried pipes, radiative and evaporative techniques.

This paper presents a statistical and persistance analysis of high ambient temperature for Athens, Greece. The paper aims to offer a procedure on the necessary calculation methodology for the statistical treatment of summer temperature data used for cooling purposes. Also it aims to offer the necessary data for a more accurate design, evaluation and sizing of cooling systems and techniques.

2. The data used

Hourly temperature data for the period 1977–1989 are taken from the National Observatory of Athens [7], (latitude = 37°58′ N, longitude = 23°43′ E and altitude 107 m). The Observatory is on a hill located at the centre of Athens and has recorded measurements of ambient temperature since 1858.

The climate of Athens is characterized as accentuated thermoMediterranean with a wet period during winter months and a dry hot period during summer. Mean monthly temperature during the summer period vary between 19 and 28 °C.

3. Statistical analysis of the data

3.1. *The frequency distribution of ambient temperatures*

Knowledge of the time period for which cooling is required in a place is of primary importance for designers of cooling systems. Information should be given on the daily distribution of cooling needs as well as on a monthly basis. Therefore, the frequency distribution of hot and very hot hours during a day as well as the general probability for a specific hour of a month being hot or very hot is necessary and very useful input.

Using the above-mentioned temperature data, the frequency for each hour of a day to present a temperature higher than 25 °C and 28 °C is given in Table 1 for all the warm period months (May to October). Values are expressed in days per month. Temperature bases equal to 25 °C and 28 °C were selected because it is accepted that they represent the lower and higher level for cooling calculations, respectively. The probability of an hour being hot, above 28 °C, is between $P=0.01$ for October and $P=0.387$ for July. this means that for July 38.7% of hours are characterized by temperatures higher than 28 °C.

The daily distribution of the mean number of days presenting a temperature higher than 25 °C or 28 °C, for each month is given in Fig. 1, with a maximum at 14:00, when the maximum daily temperature occurs. Especially for July and August and for the hours over 25 °C, high frequencies are calculated for the period between 09:00–20:00. Frequencies decreased after 20:00 and a minimum occurs at 06:00. Almost the same distribution was recorded for the variation of the number of hours over 28 °C, for the same months, indicating that during noon hours, temperatures exceeded 28 °C. A difference was observed for the night hours between 21:00 and 07:00 L.T, when the corresponding frequencies for $T=28$ °C are low.

For the rest of the summer months, it should be pointed out that slightly higher temperatures were recorded in June than September, especially during noon hours for both temperature bases. Also May is slightly hotter than October which represents climatological conditions of a fall month.

3.2. *Investigation of tendencies*

Increased emission rates of anthropogenic pollutants may be the source of important climatic changes. Recent data on the greenhouse effect [8] show that there is a non-negligible increase of the ambient air temperature. This should have a direct impact on the design and size of the cooling system. Therefore, the confidence on the existing and used multiyear mean temperature data of the mean and extreme air temperatures should be examined.

In order to investigate the probable existence of a tendency concerning the monthly number of hours over a temperature base, the non-parametric test of Spearman can be used [9]. This test is based on the estimates of the coefficient, r_s where

$$r_s = 1 - \frac{6}{n(n^2-1)} \sum (y_i - i)^2 \quad (1)$$

where $n=13$ is the number of studied years. Also $i=1, 2, \ldots$ is the real time series of the number of hours, x_i, over a temperature base. For example $i=1$ for the first and $i=13$ for the last year of the study. The parameter y_i is the rank of the corresponding x_i when data are classified in increasing order. For example $y_i=1$ corresponds to the minimum value of the time series x_i.

According to the statistical analysis [10], r_s tends asymptotically to a normal distribution with

$$E(r_s)=0 \quad \text{and} \quad \text{var}\, r_s = 1/(n-1) \quad (2)$$

where $E(r_s)$ is the mean value of r_s and var r_s is the variance of the parameter.

Therefore, using normal distribution tables, the probability a_i

$$a_i = P(|u| > |u(r_s)|) \quad (3)$$

corresponding to the value $u(r_s)$, where

$$u(r_s) = r_s(n-1)^{0.5} \quad (4)$$

is calculated.

In order to accept or reject a tendency of the time series, the value of the probability a_i is compared with the value $a_0=0.05$ which corresponds to a significant level equal to 95%.

TABLE 1. Frequencies of hourly air temperature values above the limits of 25 °C and 28 °C in Athens over the period 1977–1989 (in days/month)

	Hours																									Month
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	P	
$T>25$ °C	0.1	0.1	0	0	0	0	0	0.3	1.2	4.8	8.3	10.5	12.3	13.6	12.9	11.6	8.5	4.7	2.4	0.7	0.3	0.1	0.1	0	0.126	May
$T>28$ °C	0	0	0	0	0	0	0	0	0	0.2	1.1	2.4	2.7	2.8	3.2	2.8	1.7	0.5	0.1	0	0	0	0	0	0.025	
$T>25$ °C	3.0	2.3	2.0	1.5	1.4	1.4	2.5	7.6	15.2	21.6	24.4	26.2	26.7	27.4	27.2	26.2	25.1	22.5	17.7	11.6	8.6	6.9	5.1	3.8	0.446	June
$T>28$ °C	0.2	0.2	0.2	0.1	0.1	0.1	0.2	0.8	4.2	8.2	12.4	15.6	16.9	18.8	18.4	17.4	14.7	10.3	6.4	2.5	1.4	1.2	0.8	0.4	0.210	
$T>25$ °C	9.9	7.9	6.6	6.1	5.5	5.5	7.5	21.1	26.0	28.8	30.1	30.4	30.4	30.6	30.8	30.7	30.2	29.3	27.5	23.9	20.4	16.8	14.5	11.5	0.654	July
$T>28$ °C	1.4	1.4	1.3	1.1	1.0	0.8	1.2	3.1	10.3	19.4	24.1	25.8	27.4	27.9	27.7	27.2	26.6	22.4	17.1	8.2	5.0	3.0	2.5	1.9	0.387	
$T>25$ °C	9.5	7.2	5.5	4.2	3.6	3.5	4.8	14.5	23.6	27.9	30.1	30.5	30.7	30.4	30.8	30.6	30.4	28.5	26.3	21.9	19.3	15.6	13.1	10.8	0.613	August
$T>28$ °C	0.4	0.2	0.2	0.1	0	0	0	1.2	6.4	16.8	22.2	25.7	26.3	27.5	27.6	27.0	25.8	20.9	13.6	5.8	2.9	1.5	0.9	0.6	0.341	
$T>25$ °C	0.8	0.6	0.5	0.4	0.4	0.3	0.3	1.0	4.9	13.8	19.8	22.6	24.2	25.0	24.5	23.8	21.2	16.9	10.1	4.6	3.2	1.9	1.9	1.0	0.321	September
$T>28$ °C	0.1	0	0	0	0	0	0	0	0.5	2.2	2.2	10.6	13.8	16.3	15.9	13.6	9.8	4.3	1.6	0.6	0.3	0.1	0.1	0.1	0.136	
$T>25$ °C	0	0	0	0	0	0	0	0	0.2	0.9	2.8	4.6	5.4	6.5	6.2	4.8	3.2	1.2	0.5	0.2	0	0	0	0	0.050	October
$T>28$ °C	0	0	0	0	0	0	0	0	0	0.1	0.2	0.8	1.0	1.8	1.6	1.2	0.7	0	0	0	0	0	0	0	0.010	

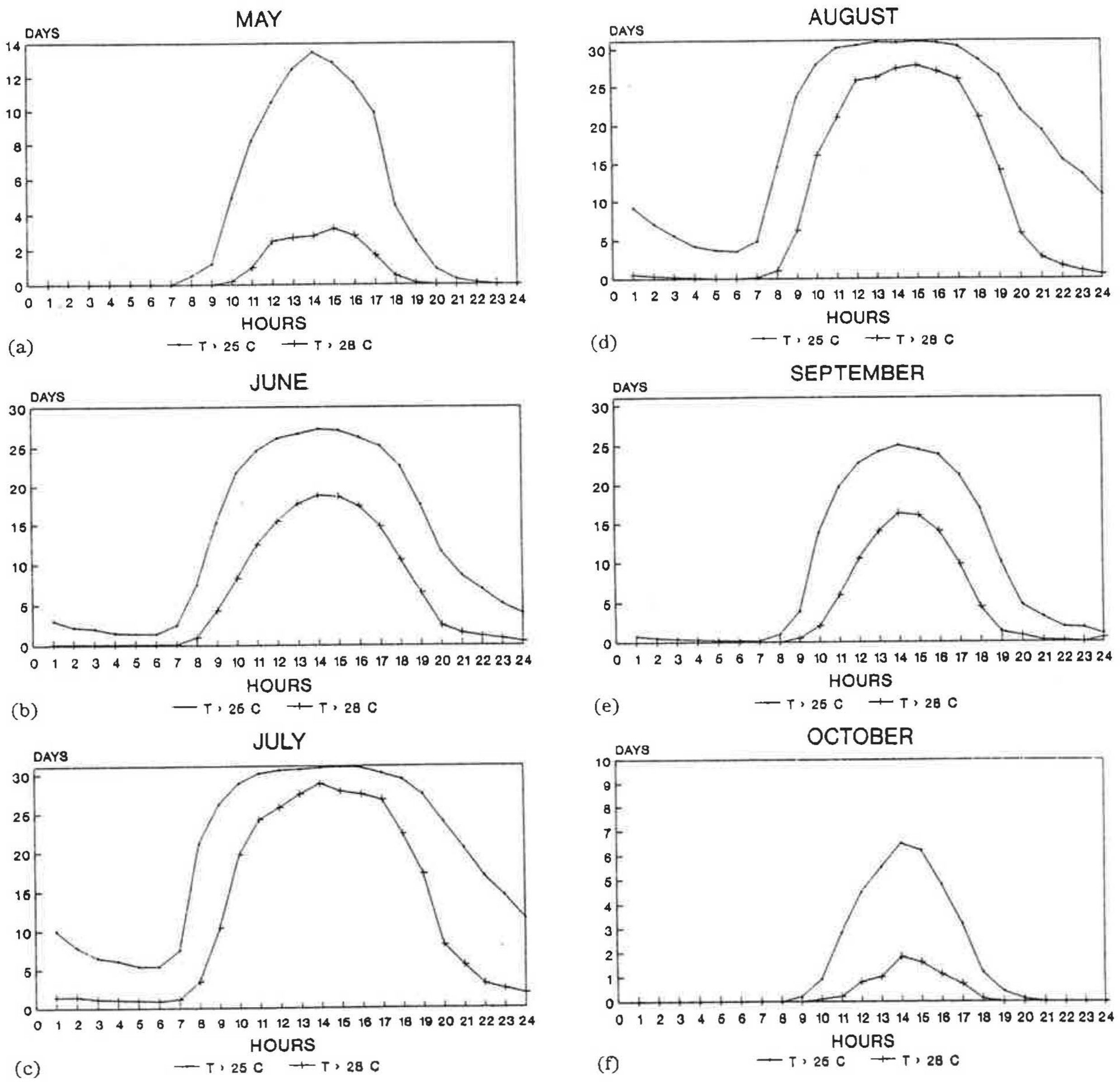

Fig. 1. Frequencies (days per month) of hourly air temperature values above the limits of 25 °C and 28 °C.

A tendency is accepted when $a_i > a_0$ and is rejected when $a_i < a_0$. When it is statistically significant, the tendency is increasing or decreasing for $r_s > 0$ and $r_s < 0$, respectively.

The calculated values of r_s, $u(r_s)$, and a_1 are given in Table 2. As it is shown, there is not any statistically significant tendency regarding the number of hours over 25 °C. Concerning the number of hours over 28 °C, a decreasing tendency is observed for June. Therefore, it can be deduced that external climatic effects, like the greenhouse effect, etc., are not sources of increasing tendencies and therefore the used data are homogeneous.

Example

In order to make clear the computation procedure of the tendency using the Spearman test, an example is given. Table 3 summarizes the procedure to estimate the existence of a tendency for June and for the hours x_i with a temperature exceeding 28 °C.

For the 13 studied years, the number of hours, x_i characterized by temperature exceeding 28 °C are calculated. Then for each year the corresponding value of y_i is assigned in increasing order. Then r_s is calculated from eqn. (1). Also from eqn. (4), the value of $u(r_s)$ is computed. Using normal distribution tables

TABLE 2. Parameters of the Spearman's tendency test

	May		June		July		August		September		October	
	>25 °C	>28 °C	>25 °C	>28 °C	>25 °C	>28 °C	>25 °C	>28 °C	>25 °C	>28 °C	>25 °C	>28 °C
r_s	0.099	0.203	−0.483	−0.665	0.115	0.297	0.473	0.549	0.484	0.533	−0.352	−0.071
$u(r_s)$	0.343	0.704	−1.675	−2.303	0.4	1.028	1.637	1.903	1.675	1.846	−1.218	−0.247
a_1	0.375	0.312	0.099	0.028	0.668	0.235	0.105	0.065	0.098	0.073	0.190	0.387

TABLE 3. An example of the computation procedure using the Spearman test for June

i (year)	Monthly hours with $T > 28$ °C, x_i	y_i
1	177	10
2	186	12
3	187	13
4	153	6
5	176	9
6	181	11
7	67	1
8	108	3
9	171	7
10	141	4
11	171	8
12	151	5
13	86	2

$r_s = -0.665$; $u(r_s) = -2.303$; $a_1 = 0.028$.

it is found that $a_i = 0.028$. The probability a_i is compared with the critical value a_0, $a_i < a_0$. Therefore it is concluded that there is no tendency of the temperature data.

4. Persistence of hot and very hot hours

Knowledge of the persistence of hot and very hot hours in a place is of high importance for the prediction of energy consumption of auxiliary cooling equipment [11]. It also helps to define the operational mode and the control of the air conditioning units. Knowledge of the persistence is required to define the limits of convective passive and hybrid cooling systems [12], while it is of primary importance for the prediction of the performance as well as of the application limits of the evaporative cooling systems [13]. Finally, prediction of the performance of ground-to-air heat exchangers which are used for cooling purposes requires knowledge of the persistence of hot and very hot hours in a place [14].

In order to calculate the persistence of hot and very hot hours, the distribution of the sequences of successive hours in a day, presenting temperatures over 25 °C and 28 °C, was tabulated and is given in Fig. 2.

For May and October it was found that the distribution of the sequences decreased for increasing spells of time. For the rest of the months, and for the hours over 25 °C, it was found that the maximum frequencies of spells occurred for 9 successive hours during June, 17 successive hours during July, 17 successive hours during August and 9 successive hours during September. For July and August, high frequencies also occurred for sequences of 24 hours. That indicates that sequences exceeding 24 hours were not detected as a result of the followed calculation procedure. Concerning the distribution of successive hours over 28 °C it was found that a maximum frequency for 9 successive hours occurred in June, a maximum frequency for 10 successive hours in July and August which corresponds to the hot period of the day (10:00–21:00), and a maximum for 6 successive hours in September. More than 24 successive hours over 28 °C occurred only during July.

From the above analysis it is deduced that there is a persistence of daily hot and very hot hours. Mathematically this is concluded if the persistence coefficient R_b, defined by Besson is calculated [9]. This coefficient takes a value equal to zero when there is no persistence and tends to infinite in the case where a persistence is observed, i.e., an event is always followed by another event. The Besson's coefficient is calculated by the expression:

$$R_b = \frac{1-P}{1-P_{i/i}} - 1 \tag{5}$$

where P is the general probability of an event as defined in Section 3 and $P_{i/i} = 1 -$ (number of hot spells/total number of hot hours).

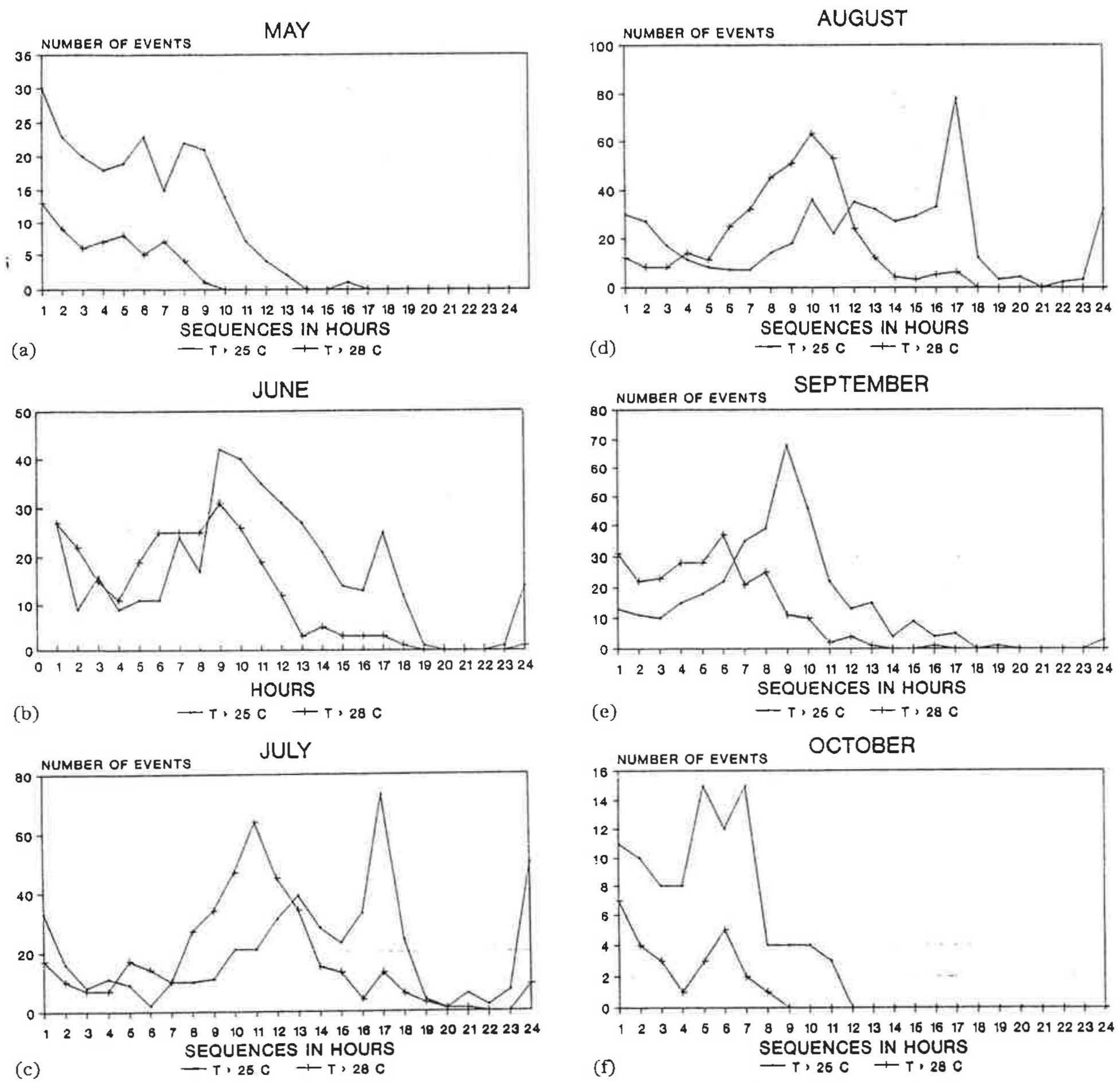

Fig. 2. Sequences of successive hours with air temperature above 25 °C and 28 °C.

Selecting the confidence limits of 95%, the persistence ratio $(1+R_b)$ is not significant when [15]:

$$\frac{1-P}{(1-P)+1.96[P(1-P)/N]^{0.5}} < R_b + 1 < \frac{1-P}{(1-P)-1.96[P(1-P)/N]^{0.5}} \quad (6)$$

where N is the total number of hours per month. However the observed values of (R_b+1) for all the cases shown in Table 4 are significantly higher than the above-defined confidence limit, therefore a significant persistence is estimated.

As deduced from Table 4, the persistence of hot hours is more important than the corresponding persistence calculated for the very hot hours, for May, June, September and October. However for July and August the contrary is observed.

For prediction reasons it is always necessary to know the duration of a hot or very hot temperature spell. Therefore, the probability, P_k, that a spell of hours above a defined temperature level, which lasted k hours will persist for at least one more hour, should be calculated. It is defined that [16]:

$$P_k = F_{k+1}/F_k \quad (7)$$

where

$$F_k = \sum_{i=k}^{n} f_i \quad (8)$$

Values of P_k for every month and for the two studied temperature bases are given in Table 5. For the temperature base of 25 °C, it is observed that P_k increases slowly until $k=2$ for May, June, September and October, where k is the duration of spells in hours. Therefore, the persistence is important only for spells until a period of 2 h.

Also, P_k increases rather quickly until $k=3$ and $k=6$ during July and August, respectively. Then P_k tends to asymptotic values. So persistence for these months is important for spells up to 3 and 6 hours, respectively.

For the upper limit of 28 °C, P_k values present a rather quickly increasing rate until $k=3$ or 4 for all months and then tend to asymptotic values. As Berger pointed out, the value of P_k may not be considered as an absolute indicator of the order of persistence [16]. The estimation of P_k values is either an indicator between months or between air temperature levels.

Example

As an example of the followed procedure, the persistence of the spells of hours above 28 °C during June is calculated.

In Table 6 the values of f_i for spells of 1 to 24 hours are given. Then the cumulative frequencies of f_i are calculated for the 24 studied spells. Finally from eqn. (7), the cor-

TABLE 4. The Besson's (R_b+1) coefficient of persistence

Temperature	May	June	July	August	September	October
T>25 °C	4.62	5.77	4.62	4.70	5.77	4.80
T>28 °C	3.85	5.64	5.91	5.78	4.48	3.62

TABLE 5. Estimation of the probability P_k that a spell which lasted k hours will persist for at least one more hour

Duration of spells (h)	May	June	July	August	September	October
For T>25 °C						
1	0.86	0.93	0.93	0.94	0.96	0.87
2	0.88	0.98	0.96	0.94	0.97	0.88
3	0.88	0.96	0.98	0.94	0.97	0.89
4	0.88	0.97	0.97	0.96	0.95	0.88
5	0.85	0.97	0.98	0.97	0.94	0.74
6	0.79	0.97	0.99	0.98	0.92	0.71
7	0.83	0.92	0.97	0.98	0.87	0.50
8	0.69	0.94	0.97	0.98	0.83	0.73
9	0.57	0.85	0.97	0.91	0.64	0.64
10	0.50	0.83	0.94	0.90	0.62	0.43
For T>28 °C						
1	0.78	0.90	0.96	0.97	0.87	0.73
2	0.81	0.91	0.97	0.98	0.90	0.79
3	0.84	0.93	0.98	0.98	0.88	0.80
4	0.78	0.95	0.98	0.96	0.83	0.92
5	0.68	0.91	0.95	0.97	0.80	0.73
6	0.71	0.86	0.96	0.92	0.67	0.38
7	0.42	0.84	0.91	0.89	0.71	0.33
8	0.20	0.81	0.88	0.83	0.54	
9		0.71	0.82	0.77	0.62	
10		0.66	0.69	0.63	0.44	

TABLE 6. Estimation of the ratio P_k for the spells of hours above 28 °C during June

i	f_i	Σf_i	P_k
1	27	276	0.902
2	22	249	0.912
3	15	227	0.934
4	11	212	0.948
5	19	201	0.905
6	25	182	0.863
7	25	157	0.841
8	25	132	0.811
9	31	107	0.710
10	26	76	0.658
11	19	50	0.620
12	12	31	0.613
13	3	19	0.842
1	5	16	0.688
15	3	11	0.727
16	3	8	0.625
17	3	5	0.4
18	1	2	0.5
19	0	1	1.0
20	0	1	1.0
21	0	1	1.0
22	0	1	1.0
23	0	1	1.0
24	1	0	
25	0		

responding value of P_k is calculated. As shown from Table 6, an important persistence is observed for $k=4$.

5. Conclusions

As shown from the data analysis, the probability of hourly temperatures during summer being higher than 25 °C is between 0.05 for October and 0.654 for July.

For the temperature base of 28 °C, the corresponding probabilities are between 0.01 and 0.387.

Due to the recent increased interest in the appearance of high summer temperatures, the tendency coefficient of the temperature time series for each summer month was calculated and it is concluded that there is no statistically significant increase in the high temperature values.

The persistence of appearance of consecutive hours with temperatures exceeding 25 °C and 28 °C is statistically significant for all the studied months. Thus the time period where cooling is requested covers a high part of the day period.

For July and August, cooling is necessary for more than five hours per day and more especially during noontime (10:00–16:00).

Nomenclature

a_i	element obtained from the normal distribution tables
n	number of observations
F_k	sum of the spells of hot hours
P	general probability of an event
$P_{i/i}$	probability that an event will occur after an occurrence on the next occasion
P_k	probability that a spell lasted k hours will persist for at least one more hour
R_b	Besson's coefficient of persistence
r_s	correlation coefficient of the Spearmans test of tendency
y_i	rank of the observation x_i when the series are classified in increasing order

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