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Analysis of the summer discomfort index in Athens, Greece, for cooling purposes

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Abstract

The discomfort index (DI) proposed by Thom is calculated for the summer period in Athens. The mean daily and hourly variations of the DI are given and analysed. The relation between high ambient temperatures and discomfort index is investigated. The probable persistence of the DI is evaluated while statistical methods have been used to analyse and predict spells of consecutive hours characterized by high values of the discomfort index.

1. Introduction

The impact of climate and prevailing weather on human comfort is almost obvious. Environmental conditions affect the heat balance between the human body and the environment and are the source of possible discomfort conditions.

Especially during the summer period, unpleasant climatic conditions have a direct impact on energy consumption of buildings for air-conditioning purposes. It is reported [1] that, due to the serious heat waves observed in Greece during 1987–1989, there is an increase of about 800% in annual purchases of air-conditioning units.

A review of the recent market data, 1976–1985, concerning sales of air-conditioning units all over the world, has shown a relative increase of about 300% representing today a market turnover of $20 billion [2]. The impact of the use of air-conditioning units on the peak electricity load is very serious. It is reported that 38% of the non-coincident peak demand in the USA is induced by air-conditioning [3].

The impact of hot conditions on human health is also very important. It is reported that during heat waves there is a serious increase of disorders due to heat [2], while there is also a great increase in mortality [4–6].

Therefore knowledge of discomfort conditions in a location is necessary for energy, and health reasons.

In order to evaluate discomfort conditions a number of human biometeorological indices have been proposed, based on various parameters such as dry-bulb temperature, humidity, air motion, radiation, clothing, metabolic rate, etc. A synoptic representation of almost thirty biometeorological indices is given in ref. 7.

The discomfort index (DI) proposed by Thom [8, 9], has known increased acceptance for practical applications and is used extensively particularly in North America [10–13].

The bioclimatic index based on a simple empirical formula permits accurate evaluation and provides information about discomfort conditions at a site. Especially for a general evaluation of the comfort conditions in outdoor spaces, where the wind speed and the radiation is spatially variable, and more complex comfort indices cannot be used, the Thom index offers valuable and accurate information which is required for comfort and energy purposes.

In this paper the variation of the Thom index is analysed during the summer period of the last 13 years in Athens, Greece, where hourly data are available. The relation between high ambient temperatures and discomfort index is investigated. The probable persistence of the DI is evaluated while statistical methods have been used to analyse and predict spells of consecutive hours characterized by high values of the DI.

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2. Variation of mean values of the Thom Discomfort Index

The American Society of Heating, Refrigeration and Air Conditioning Engineers, ASHRAE, has proposed the concept of 'effective temperature' defined as [14]: "...an empirical determined index of the degree of warmth perceived on exposure to different combinations of temperature, humidity and air movement."

Thom [9] has proposed the use of a discomfort index (DI) expressed by the following formula:

$$DI = 0.4\ (T_a + T_w) + 4.8$$

TABLE 1. Classification of the discomfort index values

DI<21 °C	No discomfort
21⩽DI<24 °C	10% of the total population feels discomfort
24⩽DI<26 °C	50% of the total population feels discomfort
DI⩾26 °C	Most of the population suffers discomfort
DI⩾26.7 °C	The discomfort is very strong and dangerous
DI>32 °C	State of medical emergency

where T_a and T_w are the dry- and wet-bulb temperatures respectively. Thom has shown that the use of the discomfort index equation produces values very close to the effective temperature over a range of T_a and T_w values common in a latitude band where Greece belongs.

A classification of boundary values of the DI indicating the degrees of discomfort is proposed also by Thom [9]. These are given in Table 1.

Data for the computation of DI values have been obtained from the records of the National Observatory of Athens, which is situated on a hill at the centre of Athens, (lat. 37.58 °N, long. 23.43 °E, and altitude 107 m). Hourly values for the period 1977–1989 and for the period of hot months, i.e., June, July, August and September, have been used.

The calculated hourly mean values of the DI for each month as well as the mean hourly value of the dry-bulb temperatures are given in Fig. 1. The hourly values of the absolute minimum and maximum values of the DI are also given in Fig. 1.

The maximum values of the mean daily variation of DI for all the studied months occur between

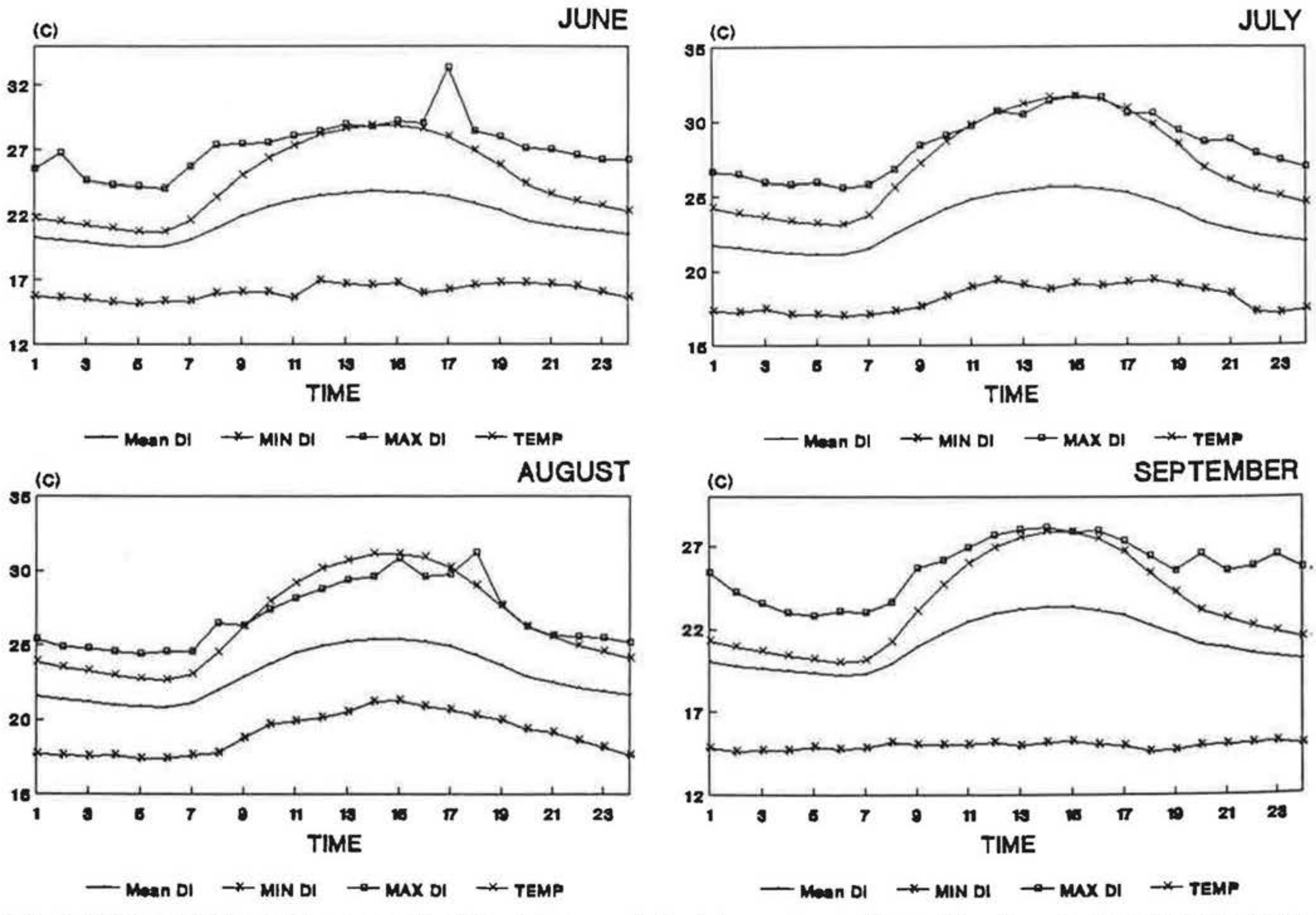

Fig. 1. Hourly variation of the mean, absolute minimum and absolute maximum DI monthly values, together with the hourly variation of ambient temperature.

14:00 and 16:00 local time. For all months the mean daily range of DI is approximately the same, (between 4.1 °C and 4.7 °C). For July and August, values of DI always exceed 21 °C. Values over 24 °C are presented between 09:00 and 19:00 for July and 18:00 local time for August, while during June and September mean hourly values never exceed 24 °C.

Maximum hourly values of DI almost always exceed 24 °C. The absolute maximum is close to 33.5 °C and is present during June. During daytime, maximum values of DI always exceed 26.7 °C. Hourly absolute minimum values are almost always lower than 21 °C.

3. Discomfort and high dry-bulb temperatures

High dry-bulb ambient temperatures are responsible for extreme discomfort conditions resulting in increased energy consumption as well as in an increased number of deaths. The heat waves in Greece in 1987 and 1988, discussed in ref. 4, present a typical example of this phenomenon.

In order to investigate the relation between high dry-bulb air temperature and discomfort conditions, the frequency distribution of temperatures higher than 28 °C as well as the frequency distribution of hours with DI > 24 °C are calculated and compared. The results are given in Fig. 2. While during the morning hours the frequency of hours with temperatures exceeding 28 °C is higher than the frequency of hours with DI > 24 °C, during afternoon hours the situation is reversed. Therefore, a persistence of discomfort conditions is observed during the afternoon hours, although the ambient temperature decreases.

TABLE 2. Besson's coefficient of persistence (R_b)

	June	July	August	September
T > 28 °C	4.64	4.91	4.78	3.48
DI > 24 °C	4.32	4.97	4.50	3.50
DI > 26.7 °C	3.58	2.67	2.35	1.93

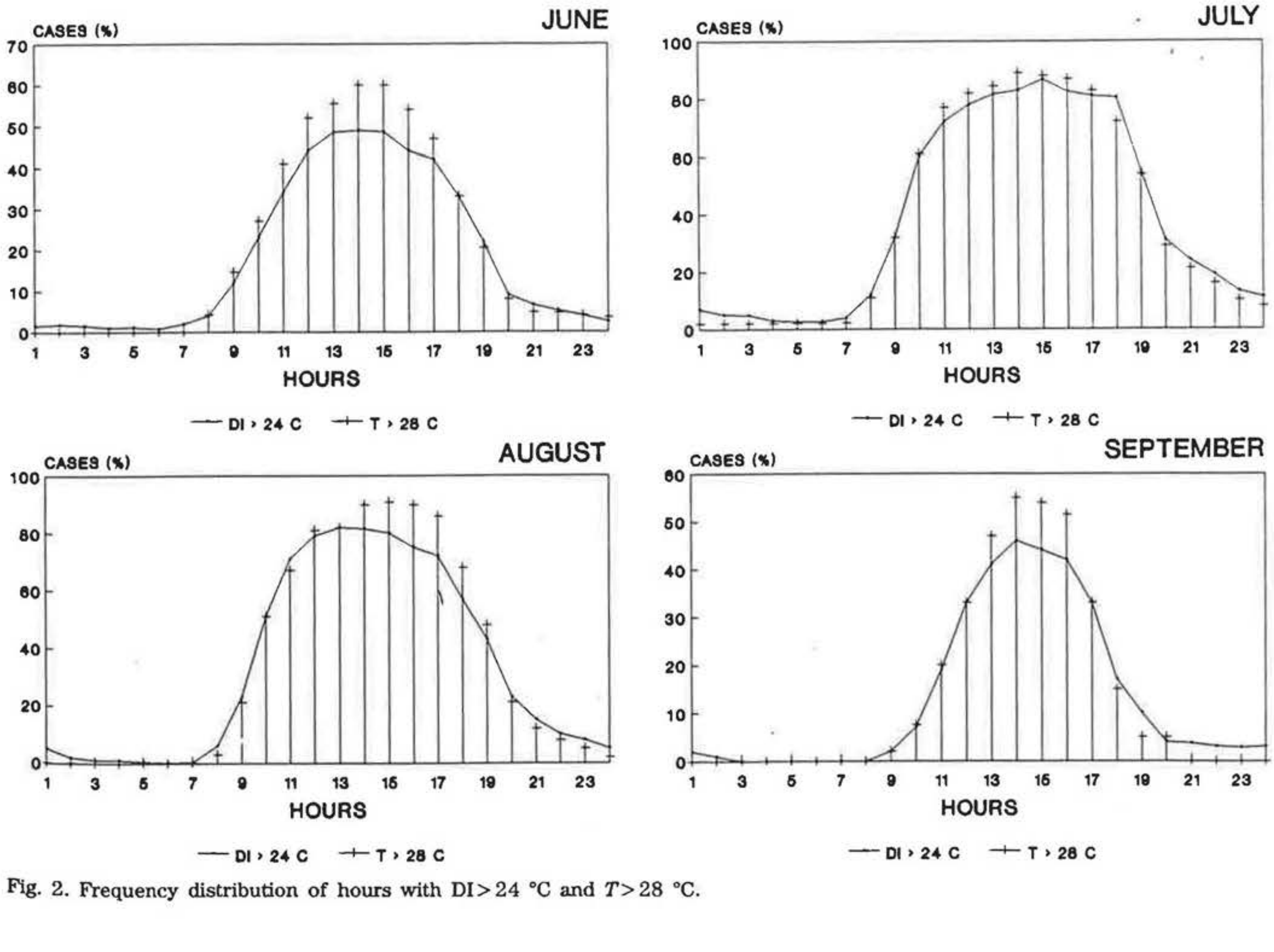

Fig. 2. Frequency distribution of hours with DI > 24 °C and T > 28 °C.

TABLE 3. Sequences of consecutive hours with $T>28$ °C, DI > 24 °C and DI > 26.7 °C

Spells (hours)	June			July			August			September		
	$T>28$	DI>24	DI>26.7	$T>28$	DI>24	DI>26.7	$T>28$	DI>24	DI>26.7	$T>28$	DI>24	DI>26.7
1	27	53	6	17	38	43	12	42	42	31	39	6
2	22	22	7	10	16	18	8	16	17	22	17	4
3	15	17	2	7	16	11	8	10	10	23	21	2
4	11	8	4	7	13	9	14	5	9	28	26	0
5	19	11	5	17	8	14	11	21	9	28	30	4
6	25	16	2	14	19	13	25	33	7	37	29	1
7	25	19	2	27	17	6	32	17	8	22	16	1
8	25	27	0	34	28	8	45	39	7	25	26	
9	31	25	3	47	11	6	51	48	5	11	13	
10	26	19	2	64	57	3	63	56	2	10	9	
11	19	18	1	45	38	1	53	29		2	5	
12	12	8	1	34	23	2	24	21		4	2	
13	3	5		15	16	2	12	11		1	2	
14	5	1		13	18	2	4	12		0	1	
15	3	3		4	11	2	3	9		0	0	
16	3	5		13	17	1	5	12		1	1	
17	1	3		6	11		6	8				
18	0	3		3	1			1				
19	0	0		0	0							
20	0	0		1	0							
21	0	0		1	0							
22	0	0		0	1							
23	0	0		0	0							
24	1	1		9	9							

TABLE 4. Parameters of linear regression analysis between spells with $T>28$ °C and spells with DI > 24 °C: ($y(\mathrm{DI}>24)=a+bx(T>28)$)

	June	July	August	September
r	0.852	0.799	0.811	0.956
a	0.085	4.793	7.974	0.582
b	0.960	0.652	0.658	0.929

In order to investigate if the observed persistence is statistically important, the persistence of ambient temperatures exceeding 28 °C analysed in ref. 15 is compared with the persistence of hours for which DI > 24 °C and DI > 26.7 °C, respectively.

For that purpose the Besson's coefficient of persistence, R_b, [16] is estimated. The calculated values for all the studied months and cases are given in Table 2. As shown, persistence is statistically important for all cases. For DI > 24 °C, R_b is calculated almost equal to the corresponding persistence coefficient for $T>28$ °C. Therefore, taking into account the higher frequency of high temperatures during morning and noon hours than the frequency of hours characterized by DI > 24 °C, it can be concluded that the observed persistence of the DI during afternoon hours is important.

In order to analyse in a more profound way the relation between high ambient temperatures and discomfort index, the sequences of consecutive hours within a day with $T>28$ °C and DI > 24 °C are calculated. The calculated sequences for all the studied months are given in Table 3. For July and August the maximum values for both the sequences $T>28$ °C and DI > 24 °C are calculated for 10 consecutive hours, while high values are also obtained for six and eight consecutive hours. For June and September the maximum values of consecutive hours characterized by DI > 24 °C are presented for sequences of one hour. However high values are calculated for sequences between six and nine consecutive hours. Maximum values in the same interval are also calculated for the sequence of consecutive hours exceeding 28 °C.

Using regression techniques it is found that a linear correlation exists between the sequences of consecutive hours with DI > 24 °C and the temperature over 28 °C. The correlation parameters a and b as well as the regression coefficients r are given in Table 4. As shown, the regression coefficient r is statistically significant in all cases at the 0.001 confidence level.

Analysis of the sequences of consecutive values exceeding 26.7 °C, has shown that the daily sequences do not exceed 13 consecutive hours, and

TABLE 5. Spells in hours with DI > 26.7 °C. Observed frequencies compared with frequencies calculated by the geometric series distribution

Duration of spells (hours)	June		July		August		September	
	Obs.	Theoret.	Obs.	Theoret.	Obs.	Theoret.	Obs.	Theoret.
1	6	7.5	43	32.0	42	33.1	6	6.1
2	7	5.9	18	24.7	17	23.7	4	4.0
3	2	4.6	11	19.1	10	16.9	2	2.7
4	4	3.6	9	14.7	9	12.1	0	1.8
5	5	2.9	14	11.4	9	8.6	4	1.2
6	2	2.2	13	8.8	7	6.2	1	2.2
7	2	1.8	6	6.8	8	4.4	1	
8	0		8	5.3	7	3.1		
9	3		6	4.1	5	7.9		
10	2	6.5	3	3.2	2			
11	1		1	2.4				
12	1		2	1.9				
13			2	1.5				
14			2					
15			2	5.1				
16			1					

TABLE 6. Calculated χ^2-test values

	June	July	August	September
χ^2 values	1.514	15.819	15.609	0.535
d.f.	3	9	6	3

are always characterized by a decreasing order.

Owing to the importance of discomfort values exceeding 26.7 °C, it is necessary to calculate the probability of spells of various lengths. From Table 3 it can be concluded that the sequences of DI > 26.7 °C follow a geometric distribution. In the geometric series model the probability of DI < 26.7 °C on an hour following k hours with DI > 26.7 °C, ($k > 1$), becomes constant.

If P_k denotes the persistence after k hours with DI > 26.7 °C the frequency function is given by:

$$f_k = F_k p_k^{(i-k)} \quad (1 - p_k)$$

where F_k are the cumulative frequencies:

$$F_k = \sum_{i=k}^{n} f_i, \qquad k = 1, 2, \ldots$$

and p_k for $k = 1$ is given by the relation:

$$p_k = 1 - \frac{\text{Sum of spells with DI} > 26.7\ ^{\circ}\text{C}}{\text{Total number of hours with DI} > 26.7\ ^{\circ}\text{C}}$$

and f_i is the observed frequency of spells of i hours long, while n is the number of hours in the longest observed spell.

The observed distribution frequencies as well as the calculated distribution frequencies using the geometric series, are given for all months in Table 5. In order to validate the accuracy of the calculated values the χ^2 test is used. As low frequencies may give an unjustified contribution to the χ^2 test, low frequencies were grouped into classes. The calculated χ^2 test values are given in Table 6.

It can be concluded that the χ^2 test is significant at a level of 0.05 for June, July and September, and at a level of 0.01 for August. Therefore, the proposed method to calculate the frequency function of spells with DI > 26.7 °C is of sufficient accuracy.

4. Conclusions

It is found that the frequencies of hours characterized by discomfort index values higher than 24 °C and 26.7 °C, which correspond to discomfort of 50% and 100% of the population, are very high for the period between June and September. While the frequency of hours with DI > 24 °C and DI > 26.7 °C follows the frequency of hours with temperatures higher than 28 °C, a persistence is observed during afternoon hours. Due to the high importance of consecutive hours characterised by high DI values, the probability of spells of various length with DI > 26.7 °C is estimated. It is found that a geometrical distribution model fits satisfactorily with data for all the studied months. Therefore, the probability of spells of consecutive hours with DI > 26.7 °C can be predicted easily and accurately.

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