Energy and Buildings, *19* (1993) 285–290

Statistical analysis of summer comfort conditions in Athens, Greece

A. Tsinonis and I. Koutsogiannakis
TEI Pireos, Thivon 250, Aegaleo (Greece)

M. Santamouris* and I. Tselepidaki
Laboratory of Meteorology, Department of Applied Physics, University of Athens, Ippokratous 33, 106 80 Athens (Greece)

(Received November 20, 1992; accepted January 6, 1993)

Abstract

Summer comfort conditions in Athens, Greece, have been analyzed statistically. The temporal variation of the number of hours inside the comfort zone as well as the corresponding frequency distribution have been calculated. The persistence of discomfort conditions has been analyzed and was found to be statistically significant for comfort and discomfort spells presented during the period May to September. The calculated duration of the spells inside or outside the comfort zone for May, July and August extend up to 20 consecutive hours, while for June and September the corresponding duration is 15 consecutive hours.

1. Introduction

Thermal comfort is defined as that condition of mind which expresses satisfaction with the thermal environment [1]. Overheating problems occurring during a warm period may cause dissatisfaction and have a direct impact on the energy consumption of buildings for air-conditioning purposes. It has been reported [2] that, due to the serious heat waves observed in Greece during 1987–1989, there was an increase of about 800% in annual purchases of air-conditioning units in the following years. Recent data from an extensive monitoring campaign including more than 1200 office, commercial and educational buildings in Greece [3], have indicated a serious impact of air-conditioning on the overall energy consumption of buildings. It was found that air-conditioning increases the overall annual energy consumption of office buildings to about 40 kWh per square metre.

Knowledge of discomfort conditions in a location is necessary in order to assess the thermal performance of buildings. Detailed analysis of the variability and the characteristics of the outdoor discomfort conditions offers the necessary input data to calculate accurately the temporal variation of the buildings performance. Lack of these data impose the use of the most commonly occurring average or extreme conditions [4] which significantly reduce the information on the dynamic behaviour of the buildings.

The increased attention to summer discomfort problems has promoted a profound analysis of the summer ambient temperatures for cooling purposes [5, 6]. The dynamic variation during summer of some common biometeorological indices [7–9] has been analyzed also in order to increase the available information on the topic. In this paper the variability of the characteristics of comfort conditions during the summer period in Athens, Greece, are analyzed. The overall analysis is based on the ASHRAE Comfort Standard 55-81 [10], which is well understood and widely used by building designers. A statistical and persistence analysis of the comfort conditions is also presented.

The present work primarily aims to provide necessary information to building and energy analysts and climatologists contributing towards more accurate analysis of the summer indoor and outdoor comfort conditions.

2. The data

Athens is characterized by a warm thermo-mediterranean climate with mild and relatively wet winters and warm dry summers. Mean ambient temperature during summer is close to 27 °C.

Hourly temperature data is taken from the National Observatory of Athens [11] (latitude = 37.58° N,

*Author to whom correspondence should be addressed.

0378-7788/93/$6.00

longitude = 23.43° and altitude 107 m). The Observatory is on a hill, located at the centre of Athens and has been recording measurements of ambient temperature since 1857.

Data for the period 1979–1988 have been used in the present analysis. As it is shown in ref. 6, these data represent satisfactorily the mean summer climatic conditions. Comparisons of the frequency distribution of the mean monthly temperature of the data of the last 130 years with the data of the studied years are in the same zone [6]. Also, it is shown that the differences between the mean temperatures of the chosen period and of the previous overlapping decades are not statistically significant.

3. Distribution of comfort hours

Considering that ambient temperature and humidity within a month are stationary parameters, hourly data for each summer month have been combined in a common set. In this way five samples for May to September have been created. Then, for each hour, it was calculated whether the climatological conditions were within the comfort zone. The summer comfort zone defined by ASHRAE Standard 55-81 has been considered [10]. This Standard sets effective temperature limits of 23 and 26 °C. The upper and lower limits of the comfort zone are bounded by lines of constant dew point temperature, with 2 °C as the lower limit and 17 °C as the upper limit. This summer comfort zone is based on sedentary or slightly active persons wearing clothing of 0.5 clo and an average air velocity of 0.25 m/s or less.

Therefore, the daily number of hours within the comfort zone, H_c, and the corresponding coefficient of variability are calculated for all the summer period. The estimated mean daily number of hours within the comfort zone, H_c, is given in Fig. 1 for all the summer months. It is found that H_c is low during the ten first days of May, while for the rest of the month it increases considerably. High values, close to 15 hours per day, are obtained during June and the first days of July. Due to the important increase of the ambient temperature observed during July and the first days of August, the corresponding values of H_c decrease considerably. For the rest of summer, the expected temperature decrease contributes to an increase in the number of hours within the comfort zone.

The mean monthly number of hours within the comfort zone, as well as the standard deviation of H_c and the mean errors of the arithmetic mean values are given in Table 1. High standard deviation values have been calculated. Also, maximum values are obtained during September ($H_c = 16.8$), while a second maximum is calculated for June ($H_c = 16.2$).

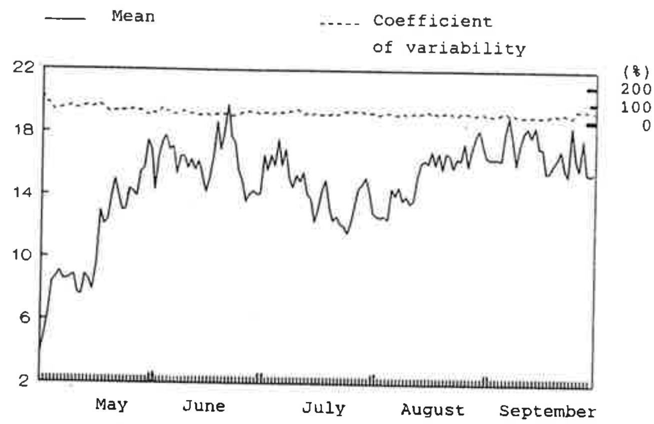

Fig. 1. Estimated mean daily number of hours (H_c) within the comfort zone for the period May to September, also with the calculated coefficient of variability.

TABLE 1. The mean number of hours with comfort conditions ($\bar{x}$), the standard deviation (s), mean error of the arithmetic mean value ($s_{\bar{x}}$), the probability of the hourly comfort conditions (p) and the Besson's coefficients of persistence (R_B)

Parameters	May	June	July	August	September
$\bar{x}$	10.8	16.2	14.4	15.3	16.8
s	5.8	4.3	4.6	3.5	3.8
$s_{\bar{x}}$	0.33	0.25	0.26	0.20	0.22
p	0.45	0.67	0.60	0.64	0.70
R_B (comfort)	4.67	3.86	4.73	4.34	3.28
R_B (discomfort)	4.57	3.79	4.73	4.38	3.29

The calculated coefficient of variability, also given in Fig. 1, does not provide important information. However, it is clear that during May the calculated variability is higher, with a mean close to 50%.

The frequency of the daily number of hours inside the comfort zone for each month is given in Fig. 2. The highest percentage of days outside the comfort zone occurs during May (8.7%). The frequency of 1–6 hours and 18–24 hours is lower than 3.2%, while between 7 and 17 hours the calculated frequency is lower (9.4%) than the corresponding frequency for the other months.

During June and September, the frequency of 0–10 hours per day inside the comfort zone is very low. The frequency of more than 20 hours inside the comfort zone is higher (2.3–8.0%), while the frequency that corresponds to periods of 11–19 hours is between 3 and 13%.

During July and August, the highest frequency of hours inside the comfort zone is calculated for periods between 11 and 20 hours as 3.2–15.2%.

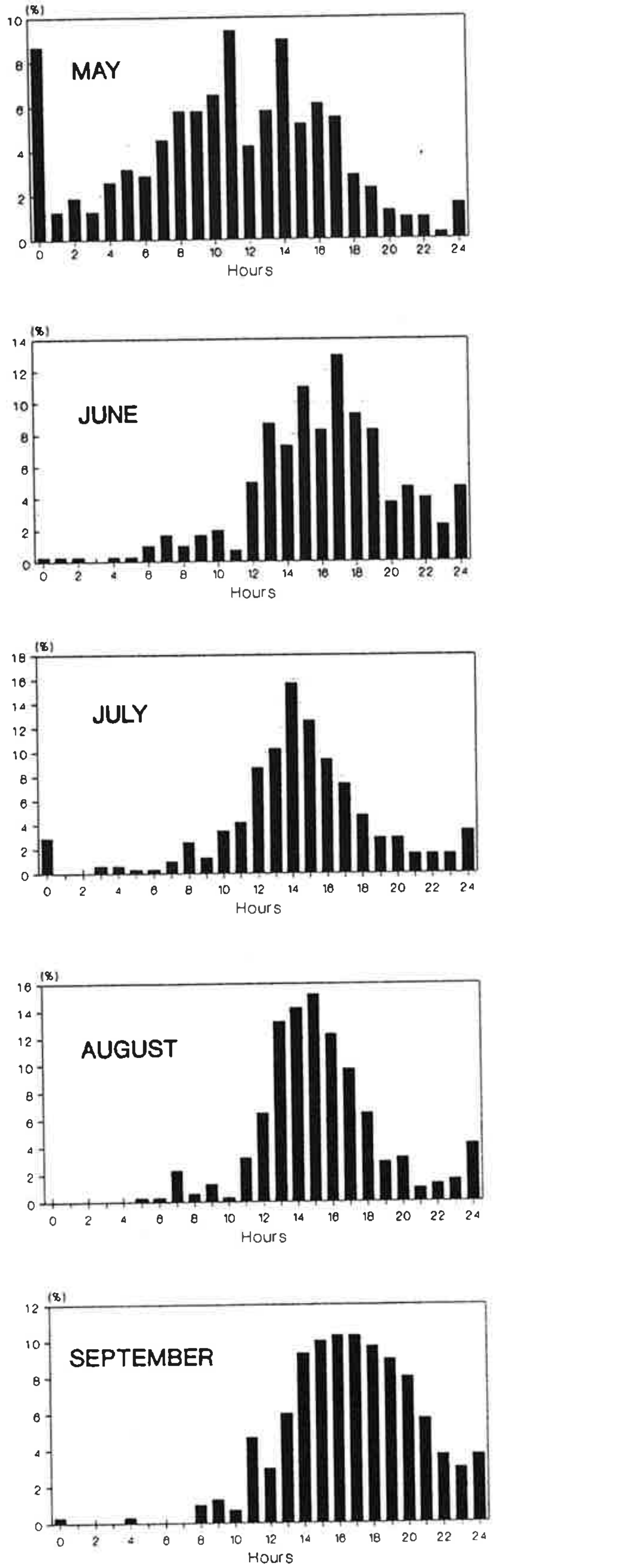

Fig. 2. Frequencies of the daily number of hours (H_c) inside the comfort zone for each month.

Knowledge of the comfort conditions in a place requires information on the daily distribution of hours within the comfort zone, H_h. The calculated values of H_h for each month are given in Fig. 3. Analysis has shown that the overall summer period should be divided into three periods.

The first period includes May, where the number of the night and early morning hours within the comfort zone is low, only 19.8%. An important increase is presented during the day where almost 60% of the hours are within the comfort zone. A decrease is then observed for the rest of the day.

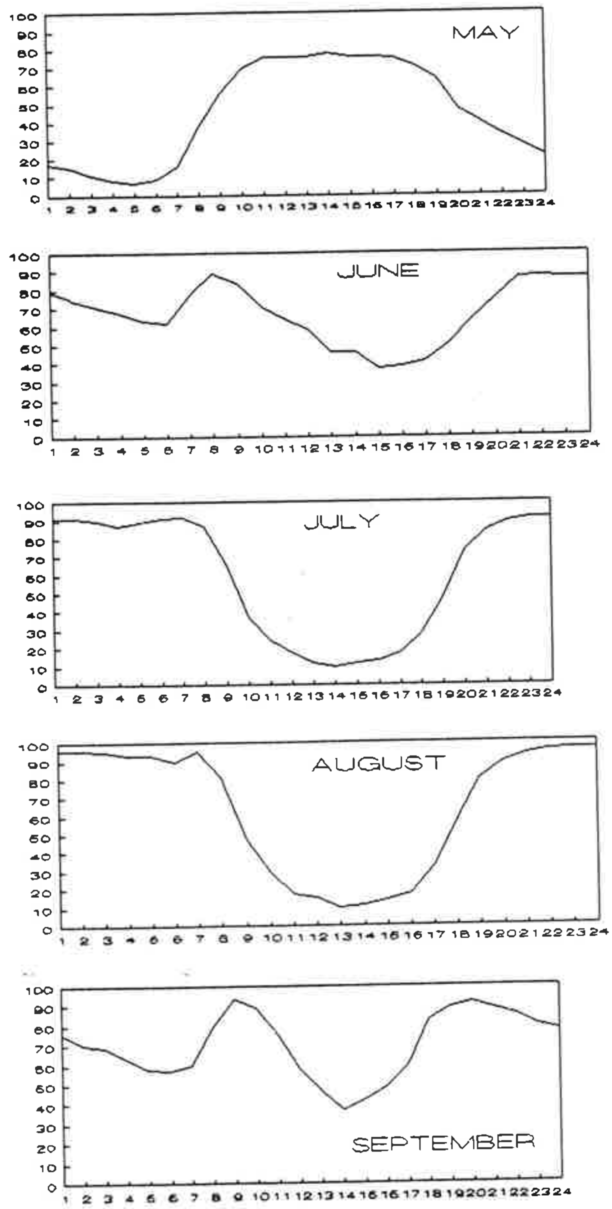

Fig. 3. Frequencies (%) per hour of the daily distributions of hours (H_h) within the comfort zone.

The second period includes June and September where the opposite situation is observed. Here, the minimum value of the hours within the comfort zone is calculated for the period 12:00–17:00 LT. This can be explained by the high ambient temperatures presented in the same time period. A second minimum is also observed during 05:00–07:00 LT where the minimum ambient temperatures are presented. However, the percentage of night hours within the comfort zone is 77.6 and 74.2 for June and September, respectively.

Finally, the third period includes July and August and is characterized by a very low number of hours within the comfort zone between 10:00–19:00 LT. During the night period for July and August, 89.7 and 93.8% of the time is within the comfort zone, respectively.

In order to obtain a more detailed analysis of the temporal variability of the comfort conditions, the overall summer time is divided into successive ten-day periods. The results obtained from such an analysis are given in Table 2. As shown, due to the high ambient temperatures, the minimum number of hours within the comfort zone is observed during 12:00–17:00 LT and during the second ten days of July and the first ten days of August. Also, due to the low ambient temperature a second minimum is also observed during the night period of the first twenty days of May.

4. Persistence analysis of the hours within the comfort zone

Knowledge of comfort and discomfort sequences as well as of the degree of persistence is necessary to evaluate climatic conditions during summer in a place. To study and to evaluate the possible persistence of discomfort conditions in Athens the following analysis has been performed.

First, the Besson's coefficient of persistence, R_B [12], has been calculated. Besson's coefficient is zero when there is no persistence and infinite when the occurrence of an event is always followed by an other occurrence. Its value can be calculated by the following expression:

$$R_B = (1-p)/(1-p_{i/i}) - 1 \qquad (1)$$

where p is the general probability and $p_{i/i}$ is the probability that a comfort or discomfort event will occur after an occurrence on the next occasion. The probability $p_{i/i}$ is equal to :

$$p_{i/i} = 1 - S/M \qquad (2)$$

where S is the total number of spells of comfort or discomfort hours and M is the total number of comfort or discomfort hours respectively.

Values of R_B for comfort and discomfort conditions have been calculated for each month and their significance is tested on 95% confidence limits. The values obtained are given in Table 1; the observed values of R_B for all months and for comfort and discomfort conditions are well above the confidence

TABLE 2. Isopleths of the number of hours in comfort zone per 10-day period.

		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
May	1st 10-days	0.6	0.5	0.3	0.2	0.2	0.3	0.3	1.4	3.0	4.5	6.2	7.2	7.3	7.8	7.3	7.1	6.7	5.4	4.0	1.7	1.5	1.2	0.9	0.7
	2nd " "	1.0	0.8	0.5	0.4	0.3	0.5	1.4	3.3	5.3	7.0	7.3	7.5	7.6	7.7	7.3	7.4	7.1	6.7	6.0	4.6	3.4	2.6	1.8	1.1
	3rd " "	3.5	2.9	2.3	1.7	1.6	1.7	2.9	6.5	8.3	9.0	9.1	8.1	7.9	7.7	8.1	8.3	8.6	8.9	8.9	7.6	6.8	5.8	5.1	4.2
June	1st " "	6.4	5.5	4.9	4.3	3.9	3.7	6.3	8.4	8.9	9.0	7.8	6.9	7.6	6.0	5.9	6.1	7.1	8.1	8.5	8.7	8.5	8.0	7.9	7.4
	2nd " "	8.2	7.7	7.6	7.2	6.8	6.8	7.8	9.3	8.4	6.5	5.0	4.0	3.7	3.0	3.5	3.7	4.4	5.8	7.2	8.8	9.0	8.7	8.6	8.7
	3rd " "	9.1	9.0	8.9	8.6	8.1	8.2	8.9	8.9	7.7	5.7	4.5	3.0	2.6	2.0	2.0	2.5	3.5	5.1	6.7	8.3	8.9	9.0	9.3	9.3
July	1st " "	8.8	8.5	8.1	8.2	8.0	8.1	8.6	9.1	7.7	5.7	4.4	3.6	2.7	2.2	2.6	3.0	3.5	4.8	6.9	8.4	8.8	9.0	9.1	9.0
	2nd " "	9.7	9.9	9.9	9.8	9.8	9.9	9.8	9.0	6.3	2.9	1.2	0.8	0.5	0.3	0.3	0.4	0.8	1.9	3.7	7.1	8.8	9.1	9.4	9.6
	3rd " "	9.9	9.0	9.0	8.9	9.0	9.2	9.2	8.5	5.9	2.8	1.6	1.0	0.7	0.5	0.6	0.6	0.6	1.9	3.6	6.5	7.7	8.7	8.7	8.8
August	1st " "	9.5	9.8	9.8	9.8	10.	10.	10.	8.6	6.6	2.5	1.0	0.2	0.1	0.0	0.0	0.0	0.3	1.2	3.2	6.4	7.8	8.7	8.9	9.4
	2nd " "	9.7	9.6	9.3	9.0	9.1	9.0	9.3	9.8	8.3	4.5	3.0	2.0	1.8	1.5	1.4	1.7	2.3	2.8	5.9	7.9	8.0	9.5	9.9	9.9
	3rd " "	9.6	9.3	9.3	8.8	8.6	8.5	8.7	8.9	9.2	6.7	4.5	2.7	2.5	1.8	1.8	2.4	2.7	5.5	7.6	9.5	9.8	9.7	9.7	9.5
September	1st " "	8.3	7.6	7.7	7.2	6.7	6.6	7.0	9.7	9.6	8.8	7.2	4.9	3.9	2.8	3.0	3.8	4.9	7.6	8.7	9.4	9.5	9.6	9.0	8.3
	2nd " "	8.0	7.5	7.6	7.2	6.8	6.5	6.5	7.9	9.2	8.6	7.1	5.4	4.2	3.4	3.7	4.6	5.9	7.8	8.9	8.9	8.8	8.5	8.2	8.0
	3rd " "	6.6	5.9	5.3	4.6	4.3	4.2	4.5	6.2	8.8	9.2	8.3	7.1	6.1	5.1	5.7	6.3	7.1	9.1	9.2	9.0	8.0	7.4	6.9	6.8

limits. Therefore, the null hypothesis of no persistence should be rejected for all cases.

Second, in order to estimate the degree of persistence, Eriksson's model [13] has been applied. Persistency by this model is tested by computing the conditional probability that hour n will be within the comfort zone or not when the state at hour zero is known. If $p_{d/c}$ is the probability to have an hour outside the comfort zone when the preceding hour was within the comfort zone and $p_{c/d}$ the probability to have an hour within the comfort zone when the preceding hour was outside, then from eqn. (2) it is obtained that :

$$p_{c/d} = \frac{\text{number of discomfort spells}}{\text{number of discomfort hours}} \quad (3)$$

$$p_{d/c} = \frac{\text{number of comfort spells}}{\text{number of comfort hours}} \quad (4)$$

where

$$p_{c/c} + p_{d/c} = 1 \text{ and } p_{d/d} + p_{c/d} = 1$$

where $p_{c/c}$ is the probability to have an hour within the comfort zone when the preceding hour was also within the comfort zone, and $p_{d/d}$ is the probability to have an hour out of the comfort zone when the preceding hour was also out of the comfort zone.

If Q_n is the probability of discomfort conditions for hour n if discomfort conditions had occurred on hour zero, q_n the probability of discomfort conditions for hour n if comfort conditions had occurred on hour zero, P_n is the probability of comfort conditions for hour n, if comfort conditions had occurred on hour zero, and p_n the probability of comfort conditions for hour n, if discomfort conditions had occurred on hour zero, then the following equations can be written:

$$Q_n = Q_{n-1}p_{d/d} + (1 - Q_{n-1})p_{d/c}$$

$$Q_1 = p_{d/d}$$

$$q_n = q_{n-1}p_{d/d} + (1 - q_{n-1})p_{d/c}$$

$$q_1 = p_{d/c} \text{ and } \lim_{n=\infty} Q_n = \lim_{n=\infty} q_n = q$$

$$P_n = P_{n-1}p_{c/c} + (1 - P_{n-1})\, p_{c/d}$$

$$P_1 = p_{c/c}$$

$$p_n = p_{n-1}p_{c/c} + (1 - P_{n-1})p_{c/d}$$

$$p_1 = p_{c/d} \text{ and } \lim_{n=\infty} P_n = \lim_{n=\infty} p_n = p$$

The values of P_n and Q_n have been calculated for each month and are given in Fig. 4. Calculations have shown that persistency of discomfort conditions loses its importance with increasing time interval from the last known state. Also, the persistency of discomfort conditions presents a tendency for higher values, 20–22 hours, for May, July and August, 16–19 hours for June and 14–16 hours for September.

The value of n for which $P_n = p_n = p$ and $Q_n = q_n = q$ indicates the length of hours over which the conditions are still 'remembering' the state of zero hour. It is calculated that the difference between P_n and p_n as well as the difference between Q_n and q_n is very small for periods of 14 to 19 hours. These

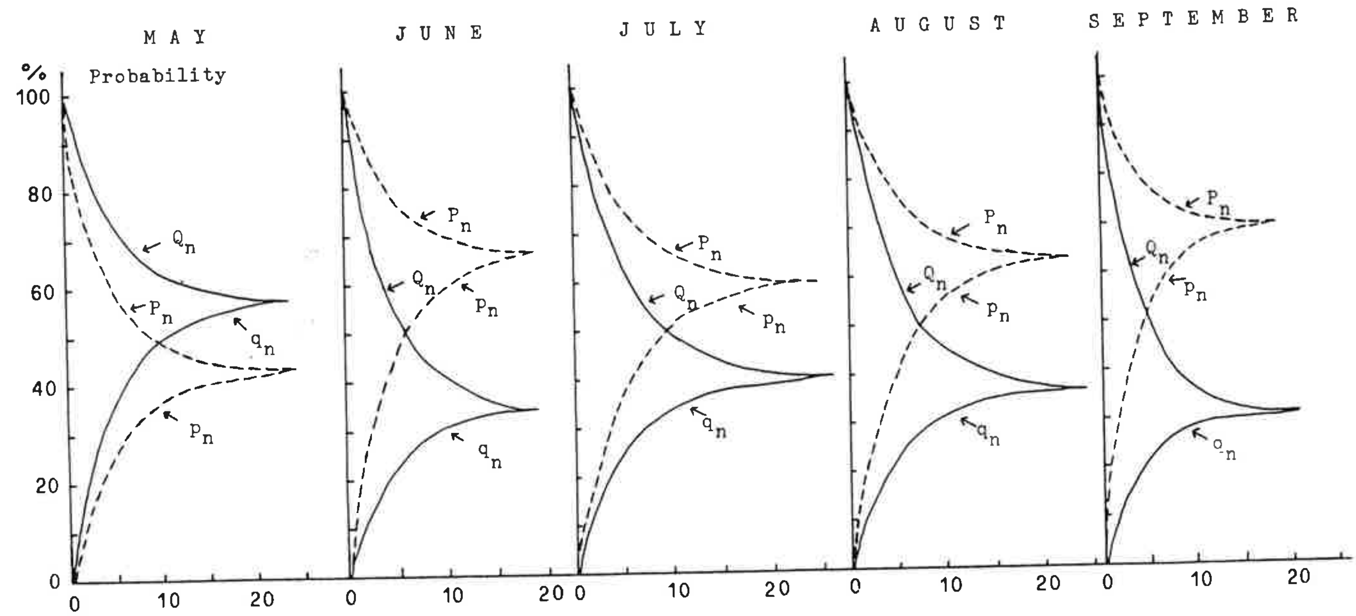

Fig. 4. The probabilities P_n, Q_n, p_n, and q_n of Eriksson's model for each of the examined months.

values indicate the high degree of persistence of the discomfort conditions.

5. Conclusions

The number of hours inside the comfort zone has been calculated for the period May to September. It has been found that during the first ten-day period of May the number of hours inside the comfort zone is low. During the period from May 11 to July 10, a significant increase of the number of hours inside the comfort zone is calculated with a mean value close to 15 hours per day. An important decrease of the comfort hours is calculated for the period between July 11 and August 10 owing to the significant increase of the ambient temperature. A significant increase of the hours inside the comfort zone is calculated for the rest of the summer period.

The highest frequencies of the hours inside the comfort zone for May are 10–16 hours per day for May, 12–18 hours per day for June, July and August, and 13–21 hours per day for September.

Calculation of the Besson's coefficient of persistence has shown that it is statistically significant for either the comfort or discomfort spells presented during the period May to September.

The duration of the spells inside or outside the comfort zone were calculated using the Eriksson model and for May, July and August extend to 20 consecutive hours, while for June and September the corresponding duration is 15 consecutive hours.

References

1 *International Standard ISO 7730, Moderate thermal environments – determination of the PMV and PPD indices and specification of the conditions for thermal comfort*, International Organisation for Standardization, 1984.

2 M. Santamouris, Natural cooling techniques, *Proc. Conference Passive Cooling, Ispra 1990*, EEC, D.G. 12.

3 M. Santamouris, A. Argiriou, E. Daskalaki, C. Balaras and A. Gaglia, Energy characteristics and savings potential in office buildings, submitted to *Solar Energy J.*, (in press).

4 M. Kolokotroni and A. N. Young, Guidelines for bioclimatic housing design in Greece, *Build. Environ.*, *25* (1990) 297–307.

5 I. Tselepidaki and M. Santamouris, Statistical and persistence analysis of high summer ambient temperatures in Athens for cooling purposes, *Energy Build.*, *17* (1991) 243–251.

6 I. Tselepidaki, M. Santamouris and D. Melitsiotis, Analysis of the summer ambient temperatures for cooling purposes, *Solar Energy*, *50* (3) (1993).

7 I. Tselepidaki, M. Santamouris, C. Moustris and G. Poulopoulou, Analysis of the summer discomfort index in Athens, Greece, for cooling purposes, *Energy Build.*, *18* (1992) 51–56.

8 C. Balaras, I. Tselepidaki, M. Santamouris and D. Asimakopoulos, Calculations and statistical analysis of the environmental cooling power index for Athens, Greece, *Energy Convers. Manage.*, *34* (1993) 139.

9 C. Balaras, I. Tselepidaki, M. Santamouris and D. Asimakopoulos, Analysis of thermal comfort conditions in Athens, Greece, *Energy Convers. Manage.*, (in press).

10 *ANSI/ASHRAE Standard 55-1981, Thermal environmental conditions for human occupancy*, American Society of Heating, Refrigerating and Air Conditioning Engineers, Atlanta, 1981.

11 National Observatory of Athens, *Climatological Bulletin*, Athens, Greece.

12 L. Besson, On the probability of rain, *Mon. Weather Rev.*, *52* (1924) 308.

13 B. Eriksson, A climatological study of persistency and probability of precipitation in Sweden, *Tellus*, *XVII* (1965) 484.