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A CLIMATIC STUDY OF AN URBAN GREEN SPACE:
THE GULBENKIAN PARK IN LISBON (PORTUGAL)*

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Abstract – Measurements of various climatic parameters were carried out in an average-sized green space in the centre of Lisbon (the Fundação Calouste Gulbenkian Park). The aims consisted of assessing the thermal differentiation between the park and the surrounding built-up area and analysing the microclimatic patterns within the park itself. The main results demonstrate that the park is cooler than the built-up area in all the seasons and both during the daytime and at night, but especially so in the daytime during the summer. The most significant microclimatic contrasts were found to occur with respect to solar radiation and mean radiant temperature, with consequences upon the level of thermal comfort. The structure of the vegetation was also found to have a significant microclimatic influence, since the reduction in the level of incident solar radiation brought on by the presence of groups of trees was much larger than that associated with isolated trees.

Key words: Urban climate, green areas, microclimate, thermal comfort, solar radiation.

Resumo – Estudo climático de um espaço verde de Lisboa: o Jardim da Fundação Calouste Gulbenkian. Foram efectuadas medições de diferentes parâmetros climáticos num espaço verde de dimensões médias no centro de Lisboa (no Parque da Gulbenkian). Os objectivos foram medir a diferença térmica entre o parque e a área urbana envolvente e analisar os padrões microclimáticos dentro do próprio parque. Os principais resultados demonstram que o parque é mais fresco do que a área construída em todas as estações, tanto durante o dia como durante a noite, mas especialmente no Verão durante o dia. O contraste microclimatico mais significativo foi encontrado em relação à radiação solar e à temperatura radiativa média, com consequências no nível de conforto térmico. A estrutura da vegetação também demonstrou ter uma influência microclimática significativa, com maior redução da radiação solar incidente sob grupos de árvores do que sob árvores isoladas.

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Palavras-chave: Clima urbano, áreas verdes, microclima, conforto térmico, radiação solar.

Résumé – Étude climatique d'un des espaces verts de Lisbonne : le parc de la Fondation Gulbenkian. Dans cet espace vert de dimension moyenne, on a mesuré divers paramètres climatiques, afin d'apprécier la différence thermique existant entre le parc et l'espace urbain périphérique, et d'analyser la répartition des microclimats à l'intérieur du parc. On observe que celui-ci est plus frais que l'aire construite périphérique, en toute saison et de jour comme de nuit, mais surtout pendant les journées estivales. Le contraste microclimatique le plus significatif affecte la radiation solaire et la température radiative moyenne au soleil, ce qui modifie le niveau de confort thermique. La structure de la végétation a aussi une influence significative, la radiation solaire étant davantage réduite sous un groupe d'arbres que sous un arbre isolé.

Mots clés: Climat urbain, espace vert, microclimat, confort thermique, radiation solaire.

I. INTRODUCTION

In biophysical, social and cultural terms, urban green spaces play a very important role in improving the quality of life and in enabling the cities to project an attractive and competitive image (Givoni, 1998; Santamouris, 2001; G.L.A., 2001; Baycan-Levent, *et al*. 2002). From the biophysical point of view, green spaces have been acknowledged as bringing about numerous climatic, hydrological and biological benefits. In a context of increasing urban and global environmental degradation, these functions assume growing importance.

This article presents the results of a climatic study undertaken in the Fundação Calouste Gulbenkian Park (henceforth GP), which is located in Lisbon (fig. 1). The choice of this park as a case-study was made in accordance with several criteria: it is a medium-sized green space (8.5 ha) located in the central part of the city of Lisbon, which renders it particularly interesting as a "case-study"; and it is a relatively flat area, which ensures that the results do not depend on the topography and can therefore be more easily generalized.

The goals of this study were twofold: a) to measure the thermal differentiation between the park and the neighbouring built-up area (local scale) both during the daytime and at night; and b) to analyse the microclimatic patterns within the green space itself during the daytime.

Although often mentioned in passing, the climatic benefits of urban green spaces are rarely accounted for, or checked against actual empirical data. In order to set the stage for the presentation of the results of this study, the following section summarises some of the previously existing research on this topic.

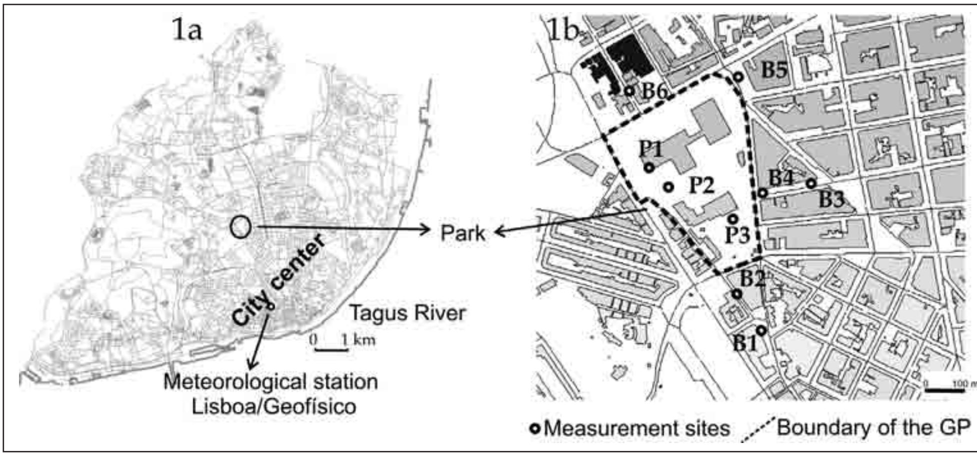

Fig.1 – Location of the GP in Lisbon (1a) and air temperature measurement network (1b)
Fig. 1 – Localização do JG em Lisboa (1a) e locais de medição da temperatura do ar (1b)

1. The climatic functions of urban green spaces

As with all other aspects that have an impact upon the urban climate, assessing the effects of vegetation requires an understanding of the influence of scale. To begin with, the effects brought on by the presence of individual plants differ from that those that are associated with large green areas (large urban parks and urban forest areas). Drawing on Oke (1987, 1989, 2004), Spronken-Smith and Oke (1998), Alcoforado (1996) and Andrade (2005), we have sought to synthesize the various climatic effects of green spaces in accordance with the climatic scale at which they occur (table I). In this classification, two different aspects were taken into account: on the one hand, the effects of the individual green spaces, regarded as "units of land use" – in this respect, their influence is largely a function of the area that they cover; on the other hand, the degree of climatic differentiation within each green space, as a function of features such as the type of vegetation, topography, etc.

As far as the climatic influence of green spaces is concerned, it is possible to identify a variety of effects, characterised by varying degrees of complexity, which occur at different scales:

- Influence of green spaces upon the radiation, energy, hydrological and momentum balances;
- Influence upon specific climatic features, such as the air temperature (*Ta*) and the wind speed (*v*);
- Combined influence of the climatic elements upon the energy balance of the human body, with consequences upon the level of thermal comfort and for human health.

Table I – Scale at which the main climatic effects of urban green spaces occur
Quadro I – Escala em que ocorrem os principais efeitos climáticos dos espaços verdes urbanos

Climatic scale	Typical size	Examples	
		Classification according to the area of the green spaces	Typical differentiation inside the green spaces
Microscale	Up to a few dozen meters	Isolated plants, tree alignments, small green spaces	Differentiation between arboreal areas and those with grass; presence of water bodies; small topographic details
Local	Between a few dozen and a few thousand meters	Medium-sized urban parks*	
Mesoscale	Several kilometres	The urban vegetation as a whole	Areas with topographical differences or subject to different conditions in terms of exposure (hills, valleys, etc)
		Large urban and suburban parks and forests	

* The GP is an example of a medium-sized green space

Table II – Main climatic changes introduced by urban green spaces
Quadro II – Principais modificações climáticas introduzidas pelos espaços verdes urbanos

Climatic elements	Type of change	Main conditioning factors	Typical scale	Characteristic values of differences between park and built-up area	Main consequences
Solar radiation balance (K^*)	Interception of $K\downarrow$ by the tree crown; change in solar radiation reflected ($K\uparrow$)	Density and characteristics of the tree crown; angle of the sunbeams; the transmissivity of a group of trees is lower than that of an isolated tree	Micro	Reduction of $K\downarrow$: – 80% to 85% for trees with leaves – 30% to 45% for trees without leaves [3]	Decrease in the daytime heating of the surfaces and buildings as well as of the human body
Surface temperature (T_s)/ thermal infrared radiation ($L\uparrow$)	Reduction	At night: *SVF*; amount of water in the soil. During the day: solar exposure; albedo; thermal conductiveness of the surfaces; amount of water in the soil	All scales	Daytime Ts differences ranging from 8ºC to 10ºC between dry and moist grass and from 16ºC to 21ºC between moist grass and asphalt surfaces[4]	Reduction of T_s, $L\uparrow$ and sensible heat flux (Q_H) emanating from the surface towards the atmosphere, buildings and human body

Bowen ratio (βw) = Q_H / Q_E	Increase in Q_E as opposed to Q_H; therefore, reduction of βw	Amount of water in the soil; solar exposure	All scales	Reduction of βw by 0.02 to 0.48 (typical values above 1 in built-up areas)[5]	Reduction of *Ts* and of Q_E to the atmosphere, buildings and human body
Air temperature (Ta)	Reduction	Size of the green space; irrigation; extension of the shaded area (during the day)	Local/ Meso	Typical cooling values ranging from 1ºC to 2ºC	Increase in the cooling of the buildingsand human body
Atmospheric moisture	Increase	Amount of water in the soil; characteristics of the vegetation; existence of water bodies	Local/ meso	Very limited differences	Reduction of Q_H from the human body to the atmosphere
Wind speed (v)	Arboreal green spaces and windbreaks cause the wind speed to decrease	Density, disposition and height of the trees; type of leaves (deciduous /evergreen); the effectiveness of the windbreaks depends on their permeability, structure, height and extension[6]	Micro/ Local	30m inside a forest, v is reduced to 60% or 80%; 120m inside it, to 7%[7]; deciduous trees within built-up areas reduce the average wind speed by between 28% and 46% in the summer and by between 12% and 41% in the winter[8]	Reduction of the heat transfer from the human body and the buildings to the atmosphere; reduction in the level of mechanical discomfort; in some situations, the conditions for the dispersion of pollution are worsened
	Wide and treeless green spaces cause the wind speed to increase	Extension and structure of the green spaces	Micro/ local	The roughness of a grassland surface is 50 to 100 times lower than that of a surface in a dense urban area	Increase in the level of heat transfer from the human body and buildings to the atmosphere; possible mechanical discomfort; in some situations, the conditions for the dispersion of pollution improve; possible increase in the levels of wind erosion of the soil and dust pollution (in the case of unkempt grasslands)

[3] Oke (1987), Geiger (1980), Rosenberg *et al*.(1983); Canton *et al.* (1994).
[4] Hal-Hemiddi (1991) cited by Givoni (1998); Ca *et al.* (1998); Spronken-Smith e Oke (1998); Spronken-Smith *et al.* (2000).
[5] Rosenberg *et al*. (1983); Oke (1987); Wilmers (1988).
[6] Rosenberg *et al*. (1983).
[7] Barry e Chorley (1992).
[8] Heisler (1990).
Q_H – Sensible heat flux; Q_E – Latent heat flux; $K\downarrow$ – Solar radiation.
L^* – Long wave radiation balance.

Alongside the aforementioned aspects, the influence of green spaces upon the levels of noise and air quality, which are important determinants of the quality of the urban atmosphere (Givoni, 1998; Beckett, *et al.;* 1998, Kuttler and Strassburger, 1999 and Upamnis, *et al*. 2001; Fang and Ling, 2003, 2005), are also commonly acknowledged. These latter aspects are not addressed in this paper.

Table II presents an attempt to synthesize the main climatic changes associated with urban green spaces.

The effects upon the wind conditions are complex: besides affecting the wind speed, we find that the larger green spaces that are characterised by pronounced thermal contrasts *vis-à-vis* the surrounding areas can, on stable nights, give rise to local advection (on the topic of breeze parks, see Oke, 1987 and 1989; Eliasson and Upmanis, 2000).

In sum, the main climatic changes brought about by green spaces consist of their cooling influence upon buildings, the atmosphere and the human body (even though the changes to the wind speed and the increase in the level of atmospheric moisture can have the opposite effect). For this reason, they play a particularly useful role in the summer, in urban areas and, above all, in a context of global heating. However, one should bear in mind the importance of avoiding simplistic, one-size-fits-all solutions that do not draw on an adequate understanding of the underlying mechanisms, since those solutions are often ill-suited to both the specific context and the intended objectives.

II. MATERIALS AND METHODS

1. Local scale

In this research, the GP was considered as a unit of land use, and, as such, differentiated with regard to the surrounding built-up area. We have sought to ascertain whether differences could be identified in terms of the thermal behaviour in the two areas.

In order to do this, fixed *Ta* sensors (table III) were placed in several different sites both inside and outside the park (fig. 1b; fig. 2; description of sites in table IV), during the periods indicated in table V. Measurements were undertaken throughout 117 summer days, 10 autumn days and 12 winter days. For this reason, the results for the summer period should be regarded as statistically more significant than those for the other seasons. In addition, the two summer periods during which the measurements were carried out included a wide variety of weather types, namely several rainy and cloudy days in August 2004 and some very hot days in July 2004 and August 2005 (the maximum temperatures recorded at Lisboa/Geofísico (fig. 1a) were 37.1ºC on July 27th, 2004 and 38.2ºC on August 4th, 2005).

Ta was recorded at 10-minute intervals, but the analysis of the data was based on their 30-minute average in order to enhance the consistency of the results.

Table III – Measurement devices used for collecting data at the GP
Quadro III – Aparelhos de medição utilizados para recolha de dados no GP

Parameter	**Device**
Air Temperature (*Ta*)	*TinyTalk* Sensor and data logger – Gemini Data Loggers
Relative humidity (*HR*)	*Rotronic A1* Termohygrometer
Wind speed (*v*)	*Kestrel 3000 Neilsen-Kellerman* Anemometer
Solar radiation (*K*)	*CM 21 Kipp & Zonen* Pyranometer
Infrared radiation (*L*)	*CG1 Kipp & Zonen* Pyrgeometer

Table IV – Characterization of the measurement sites
Quadro IV – Caracterização dos locais de medição

Site	**SVF**[1]	**Period with direct solar radiation on August 1th**	**Site Characteristics**
P1	0.79	7am – 8pm	Over the green terrace of a building, around 6m above the topographical surface
P2	0.16	–	Under dense tree cover
P3	0.49	6am – 10am; 16am – 19am	Average tree density
B1	0.60	6am – 13pm	Small urban square; site exposed to the East
B2	0.53	6.30am – 13pm	NW-SE street; site exposed to the East
B3	0.29	7.30am – 14pm	E-W street with trees; site exposed to the South
B4	0.61	7am – 19pm	Street corner
B5	0.75	8am – 8pm	Open area near the GP boundary
B6	0.48	7.30am – 2pm	NW-SE street; site exposed to the East

[1] SVF = Sky View Factor

Table V – Measurement periods of Ta
Quadro V – Períodos de medição da Ta

Summer	June 23rd – September 12th, 2004
	July 25th – August 29th, 2005
Autumn	September 28th – October 7th, 2004
Winter	January 12th – 24th, 2005

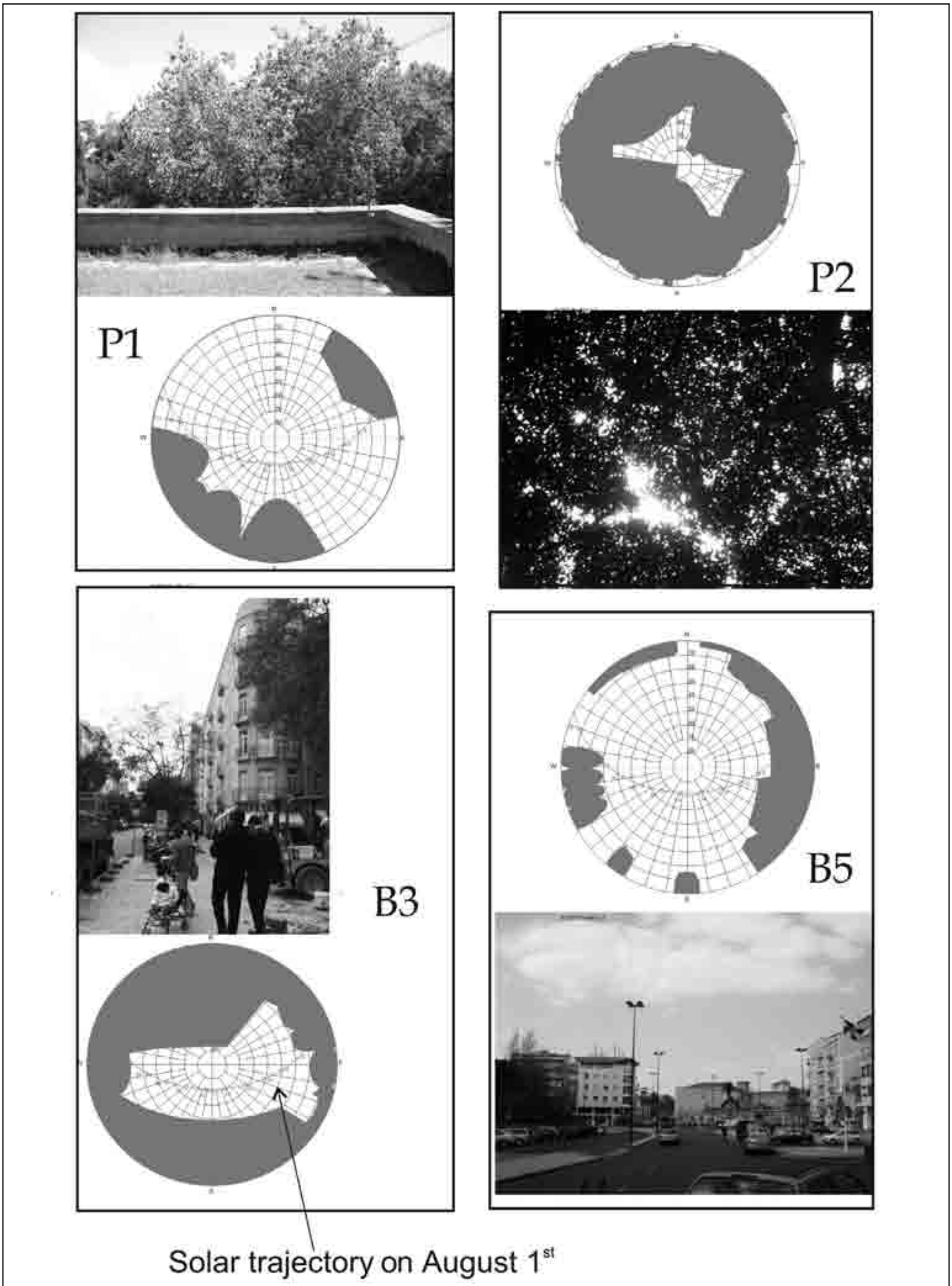

Fig. 2 – Solar diagrams and photographs of some of the measurement sites
Fig. 2 – Diagramas solares e fotografias dos locais de medição

2. Microscale

The second part of the study was based on itinerant measurements of *Ta*, *HR*, *v*, *K* and *L* in ten different sites located within the park. The measurements were undertaken in the summers of 2004 and 2005, during the daytime – the time when the Park is subject to greatest use. We have sought to assess not only the variation in the measured climatic features, but also the combined influence of those elements upon the human body, in accordance with the concept of Physiological Equivalent Temperature (PET – Mayer and Höppe, 1987; Höppe, 1993, 1999; Matzarakis, Mayer and Iziomon, 1999). This enabled us to reach a number of conclusions with regard to the level of thermal comfort of the park's users. A discussion of the problems associated with the use of the PET in the context of Lisbon's climate can be found in Andrade and Alcoforado (in press).

III. RESULTS

1. Local scale

The daytime and nighttime periods were analysed separately. Many studies of the thermal behaviour of green spaces have focused exclusively on the nighttime period, since it is at this latter time that the urban heat island phenomenon is at its highest (Oke, 1987; Alcoforado, 1992; Alcoforado and Andrade, 2006). However, from the point of view of the users of green spaces, the daytime period is clearly more important.

1.1. *Daytime period*

The analysis of the daytime conditions refers to the following periods. In the summer between 9am and 6.30pm; in the autumn between 9am and 6pm; in the winter between 10am and 5pm.

Table VI summarises the main thermal effects associated with the presence of the park. In order to compare the park with the surrounding built-up area, the following parameter was used:

$\Delta\ med_t = med_{ut} - med_{vt}$
where:
$\Delta\ med_t$ = difference between the medians of *Ta*, at time t
med_{ut} = median of *Ta* in the surrounding built-up area at time t
med_{vt} = median of *Ta* in the Park at time t.

This parameter reflects the overall thermal behaviour of the green space as compared to the surrounding built-up area, while controlling for the specificities of the various different measurement sites. The use of the median enabled us to circumvent the effect of the extreme values of *Ta*, as well as that of missing data due to technical problems – both of which usually affect the mean more than they affect the median.

On the other hand, the parameter consisting of the maximum spatial differences between the park and the surrounding built-up area at any given moment ("park cool island" – Spronken-Smith and Oke, 1998) can also be used to characterise the thermal influence of the green space:

$\Delta\ max_t = Tmax_{ut} - Tmin_{vt}$
where:
$\Delta\ max_t$ = maximum difference at time t
$Tmax_{ut}$ = highest Ta in the built-up area at time t
$Tmin_{vt}$ = lower Ta in the park area at time t.

Two series of values were thus produced, for Δmed_t and Δmax_t respectively. The statistical characterization of these two series is presented in table VI.

Table VI – Statistical characterization of the differences in *Ta* between the park and the surrounding built-up area in the daytime period
Quadro VI – Caracterização estatística das diferenças de Ta entre o Jardim e a área construída envolvente no período diurno

	Δmed_t							**Δmax_t**						
	Percentiles (ºC)							**Percentiles (ºC)**						
	n	**Mini-mun (ºC)**	**15th**	**50th**	**85th**	**Maxi-mum (ºC)**	**%>0**	**n**	**Mini-mum (ºC)**	**15th**	**50th**	**85th**	**Maxi-mum (ºC)**	**%>0**
Summer	1809	-3.5	0	1.3	**2.9**	**5.4**	83	1630	-3.2	2.2	**4.1**	**5.8**	**9.5**	100
Autumn	218	**-0.1**	**0.9**	**1.8**	2.7	4.6	**100**	218	**0.8**	**2.4**	**4.1**	5.5	7.5	100
Winter	117	-1.6	-0.7	0.12	0.49	0.9	56	117	0.2	0.7	1.4	2.3	3.7	100

In the summer, the daytime median temperature in the Park was lower than that in the surrounding built-up area in 83% of the cases: the median difference exceeded 1.3ºC in 50% of the cases and 2.9ºC in 15%. The effect in terms of thermal differentiation during the autumn was similar to that in the summer, which was due to the fact that the short autumn data-collection period was characterised by anticyclonic conditions and high temperatures. In the winter, the median differentiation was much less significant, and the thermal conditions in the green space could hardly be distinguished from those in the surrounding area.

Turning our attention to Δmax_t, we find that, in almost 100% of the observations and regardless of the time of the year, the measurement sites located outside the green space were hotter than those inside it. The largest differences, reaching as much as 9.5ºC, occurred in the summer.

The situations in which the thermal impact of this green space was most significant consisted of very hot days (with temperatures nearing 40ºC) characterised by clear sky and weak wind from the NE (typical conditions for the occurrence of heat waves in Lisbon). As might be expected, under these conditions the lowest temperatures (30ºC to 33ºC) were recorded in those parts of the park that were under dense shade. The values of Ta in the P1 site, which is located inside the park and is subject to many daily hours of solar exposure (fig. 2), were very similar to those recorded in the surrounding built-up area.

The thermal differences between the measurement sites are strongly associated with their degree of exposure to direct solar radiation. Sites in the shade and sites under the sun were selected both inside and outside the park, and those sites that were located under the sun inside the green space tended to be hotter than those that were located in the built-up area but in the shade. With the aim of ascertaining the influence of the green space upon the Ta while controlling for the degree of exposure to the sun, a comparison was made between sites characterised by similar exposure conditions in the two areas (inside and outside the park).

Figure 3 provides a clear indication of the influence of the green space upon the temperature of the sites in the shade inside the park, as compared to those located outside the park (table IV). Site P2 was around 5.0ºC cooler than site B3 during most of the afternoon period, and 0.9ºC-1.6ºC cooler than site B6 (which was the second coolest).

If we instead examine the values for the sites under the sun, we find that those located inside the Park were clearly cooler, particularly in the afternoon period (fig. 4): the differences were especially significant after 4pm. The temperature figures were highest in the B4 site, which is located outside the park and close to a wall facing west: the median difference compared to the P1 site was 2.2ºC at 5pm. In the morning period (fig. 4), the temperatures in the P1 and B5 sites were very similar: the values of the Ta recorded in the two sites cannot be statistically distinguished. The sites furthest away from the Park (B1 and B6) tended to be the hottest: their proximity to walls facing south contributes to the high temperatures recorded in these sites.

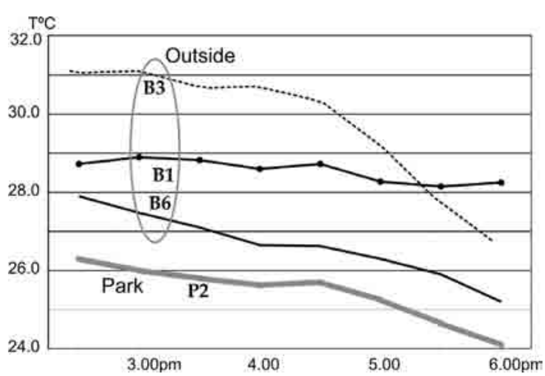

Fig. 3 – Median air temperature in sites in the shade, during summer afternoons
Fig. 3 – Temperatura mediana do ar nos locais à sombra, durante as tardes de verão

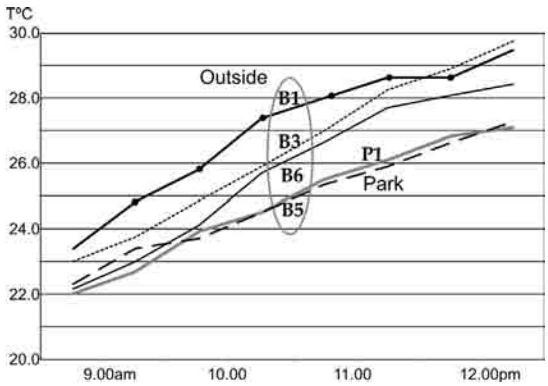

Fig. 4 – Median air temperature in sites under the sun, during summer mornings
Fig. 4 – Temperatura mediana do ar nos locais ao Sol, durante as manhãs de Verão

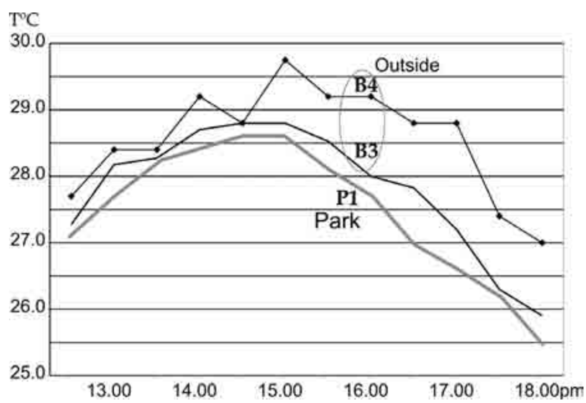

Fig. 5 – Median air temperature in sites under the sun, during summer afternoons
Fig. 5 – Temperatura mediana do ar nos locais ao Sol, durante as tardes de Verão

1.2. *Nighttime period*

The following periods were considered in the analysis of the nighttime conditions: in the summer and autumn, between 11pm and 5am; in the winter, between 9pm and 7am. The statistical analysis of the differences between the measurement sites (table VII) was similar to that for the daytime period. In terms of the Δmed_t parameter, we find that the park was almost always cooler than the surrounding built-up area, even though the differences were relatively small: in the summer, the difference exceeded 1ºC in only 15% of the cases. Naturally, the Δmax_t parameter was higher: in the summer periods, it exceeded 1.4ºC in 50% of the cases and 2.5ºC in 15% of the cases.

Table VII – Statistical characterisation of the differences in Ta between the park and the surrounding built area in the nighttime period
Quadro VII – Caracterização estatística das diferenças entre o Jardim e a área construída envolvente, no período nocturno

	Δmed_t							Δmax_t						
	Percentiles (ºC)							**Percentiles (ºC)**						
	n	**Minimun (ºC)**	**15th**	**50th**	**85th**	**Maximum (ºC)**	**%>0**	**n**	**Minimun (ºC)**	**15th**	**50th**	**85th**	**Maximum (ºC)**	**%>0**
Summer	555	-0.3	0.3	0.7	1.0	2.0	96	487	0.5	0.9	1.4	2.5	4.1	100
Autumn	70	**0.34**	**0.5**	**0.8**	**1.6**	**2.1**	100	70	**0.77**	0.88	1.36	2.67	3.3	100
Winter	130	-0.1	0.1	0.4	1.4	1.77	95	130	0	0.3	0.74	2.34	3.9	98

Four different sites, representing four different micro-environments, were compared: sites P1 and P2 inside the Park (table IV, fig. 2) and sites B3 and B5 outside the Park.

The median temperature was computed for every hour of the nighttime period (fig. 6). The two sites located outside the Park experienced temperatures above those recorded inside the green space: the median difference between site B3 and the Park was 0.9ºC, and between site B5 and the Park, 0.5ºC. The difference between sites B3 and B5 was found to be a consequence of the difference between the two sites' *SVF* (0.75 in site B5; 0.29 in site B3), and, consequently, of the differences in radiation balance between the two sites. The fact that site B3 is further away from the Park and sheltered from the wind may also have contributed to the thermal difference. Site P2, located inside the Park and under dense tree cover (fig. 2; SVF = 0.16), was cooler than site B5 (SVF = 0.76) in 83% of the cases, with a median difference of -0.5ºC. The difference between the two sites was found to be statistically significant (F = 27.3, for a critical value of 3.8 at a level of significance of 0.95). The previous figures refer to the summer period; in the winter, the difference between the two sites was not found to be statistically significant (F = 0.31, for a critical value of 3.8 at a level of significance of 0.95). This means that in the summer considerable evaporative cooling takes place inside the green space (even during the night), which causes the site inside the park to be cooler despite its lower SVF; in the winter, by contrast, the effect of the SVF is relatively more important, especially in those nights in which there is radiative cooling: in 10% of the coolest periods, site B5 was cooler than site P2, but warmer than site P1 (which has a SVF of 0.79).

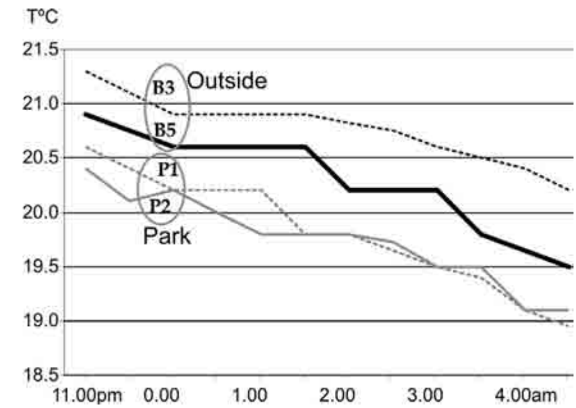

Fig. 6 – Median air temperature during summer nights
Fig. 6 – Temperatura mediana do ar, durante as noites de verão

Overall, there was virtually no difference in the Ta between sites P1 and P2; thus, this parameter did not reflect the difference between these two sites in terms of *SVF* (table IV). The difference between the series for the two sites was not statistically significant (F = 0.21, for a critical value of 3.8 at a level of significance of 0.95); however, if we consider only the five coolest nights (in which there was intense radiative cooling) in the summer and the winter (fig. 7), we find that the P1 site was almost always cooler, even though in the summer this difference only became significant after 11.30pm (and increased throughout the night).

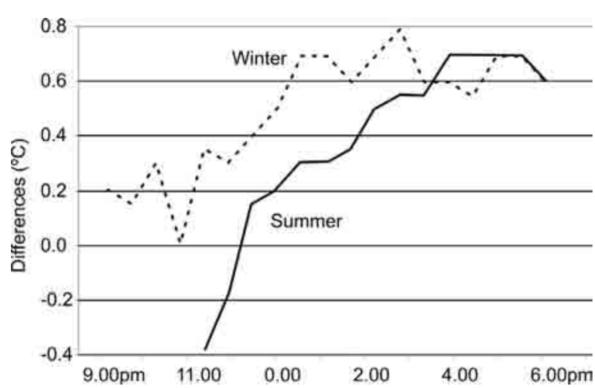

Fig 7 – Median differences between sites P1 (open) and P2 (dense tree cover), in the 5 coolest nights of each season
Fig. 7 – Mediana das diferenças entre os locais P1 (aberto) e P2 (cobertura arbórea densa), nas 5 noites mais frias de cada estação do ano

2. Microclimatic study

Clearly, the main factor behind microclimatic differentiation is the degree of exposure to direct solar radiation (*K*↓). Figure 8 presents a synthesis of the differences between the measurements undertaken in sites located in the shade and in those located under the sun. As might be expected, the greatest differences found between the sites in the shade and those under the sun are in terms of global K (an average 88% reduction of K↓ in the sites in the shade, with values ranging between 97% and 70%), even though the sites in the shade are also characterised by higher levels of L↓ (and of the infrared balance *L**). The overall result is a much higher radiation balance (*Q**) and higher T_{mrt} in the sites exposed to direct solar radiation. The average difference in the *Ta* is much lower (a mere 4.0ºC); however, the difference in the PET exceeds 18ºC.

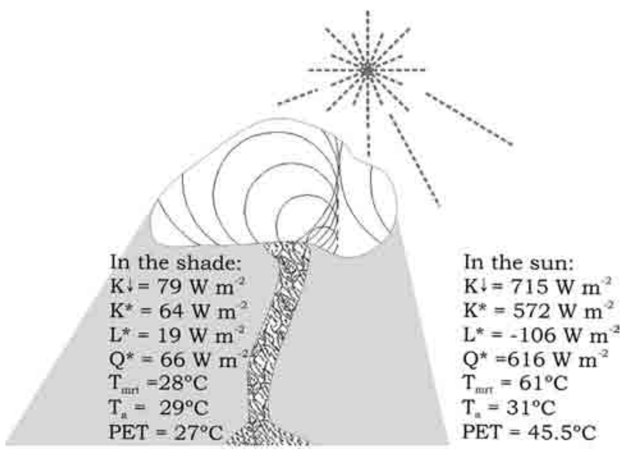

Fig. 8 – Median of the results of the measurements made in the sun and in the shade
Fig. 8 – Mediana dos resultados das medições à sombra e ao Sol

The reduction in K↓ and T_{mrt} was much more significant in those sites that are located under groups of trees than in those located under isolated trees: in the case of the site represented in figure 9a, the average reduction in *K*↓ was 94% and the T_{mrt} was 26ºC, whereas in the site depicted in fig. 9b, the average reduction in *K*↓ was 76% and the T_{mrt} was 33ºC. These differences are largely due to the lateral fluxes of diffuse *K*: under isolated trees, *K*↓ was 4.1 times higher than under groups of trees, but the lateral fluxes were 9 times as high.

Fig. 9. Measurement sites of solar radiation:
9a. under a dense tree cover; 9b. under an isolated tree
Fig. 9 – Locais de medição da radiação solar:
9a. sob cobertura arbórea densa; 9b. sob uma árvore isolada

These radiation measurements were carried out when the trees were totally covered with leaves. Naturally, the results in the colder part of the year can be very different in the case of deciduous trees. Radiation measurements undertaken in the same Park in the winter of 1998 showed that under a cover of deciduous trees, the reduction in $K\downarrow$ varied between 95% and 56% throughout the winter. This variation was attributed to two factors: the decrease in the level of tree cover as the winter progressed, and the increase in the height of the sun, allowing for greater sunbeam penetration. These results are consistent with the conclusion that (contrary to what is commonly considered) deciduous trees can constitute a significant barrier to solar radiation even in the winter (Rosenberg, *et al.*, 1983; Oke, 1989; Canton, *et al.*, 1994), and especially so in climates characterised by mild winters (Canton, *et al.*, 1994).

IV. DISCUSSION AND CONCLUSION

The conclusions to be drawn from this study concern, on the one hand, the local differentiation between the Park and the surrounding built-up area, and, on the other, the microclimatic differentiation within the Park itself. This green space was cooler than the surrounding built-up area in all seasons, but especially so during the summer. In this latter season, during the daytime, the median difference amounted to 1.3ºC and the maximum difference exceeded 4.1ºC in 50% of the cases. The park was particularly cool (in relative terms) under very hot weather conditions (mean local temperature above 35ºC), when the extreme difference exceeded 9ºC. These observations support the conclusion that green spaces play an important role in mitigating situations of extreme heat.

The aforementioned differences did not control for the differences in terms of solar exposure; sites in the shade and sites under the sun were selected both inside and outside the GP, and it goes without saying that, during the summer, the sites under the sun were always hotter, regardless of their location. However, it was found that, under similar solar exposure conditions (sun/shade), the sites inside the GP were almost always cooler than those located outside the park: the difference between the sites under the sun located inside and outside the park reached 2ºC to 3ºC; in the case of the sites in the shade, the difference was as high as 5ºC.

During the nighttime period, the park was also almost always cooler than the surrounding built-up area, but the differences were less significant: the median difference in the summer amounted to 0.7ºC, and extreme differences above 1.4ºC were found in 50% of the cases. Within the Park, there was little thermal differentiation during the nighttime period, but in nights characterised by intense radiative cooling, open spaces were found to have a considerable cooling effect.

According to several authors, the size of green spaces is an important determinant of their thermal differentiation effect, and should accordingly be taken into account by urban planners. The significant thermal effect of large parks has been abundantly demonstrated (Jauregui, 1990/91; Barradas, 1991; Spronken-Smith and Oke, 1998; Upmanis, *et al*, 1998; Yu and Hien, 2006). The GP, which covers an area of 8.5 ha and can therefore be considered a medium-sized green area, has a clearly significant thermal impact, even though its thermal influence upon the surrounding built-up area could not be proven beyond doubt (it is probably rather insignificant). The thermal impact of small green areas is more doubtful, even though Saito *et al.* (1990/91), for example, found significant cooling occurring in a park of only 0.4 ha. Previous measurements carried out in Lisbon produced similar results (Alcoforado, 1996); not only are some exogenous factors (such as the specific measurement techniques used, the weather types and the size of the samples) likely to influence the results, it also seems impossible to establish a linear relationship between the size of the parks and the thermal differentiation associated with them, due to the fact that the latter is highly dependent upon the structure of the vegetation, the topography and the characteristics of the built-up area. Still, it is worth pointing out that even though small green spaces may not have a significant thermal influence, they do perform other microclimatic (as well as biophysical and social) functions, such as reducing the solar radiation at the surface level (Hoyano, 1988; Oke, 1989; Matzarakis and Mayer, 1998; Barradas, 2000).

The main microclimatic differences within the Park itself during the daytime concerned the levels of solar radiation and Tmrt: K↓ in the shade was on average 12% that recorded in the sites under the sun, and T_{mrt} was 33ºC lower; the average difference in Ta was only 2ºC. The reduction in the level of solar radiation under groups of trees was also significant. These results clearly demonstrate the importance of shade in the summer, although one should bear in mind that, in the winter, shades do not have a positive climatic effect. All these conclusions provide evidence to support the importance of ensuring, and adequately planning for, the microclimatic diversity of green spaces.

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