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ORIGINAL ARTICLE

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The urban heat island in a small city in coastal Portugal

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Abstract This project arose from the need to study the phenomenon of the urban heat island, since only by recognising this phenomenon can we moderate it to improve the human and urban environments. Not only big cities develop urban heat islands. This study detected the presence and recorded the characteristics of an urban heat island in the small coastal city of Aveiro, Portugal. The study was developed through the scheduled measurements of air temperature and the analysis of the geographical, meteorological and urban conditions. The form and intensity of Aveiro's heat island are a response to the interaction of three principal factors: the urban morphology (the hottest zones in the city are those with the tallest and the highest density of buildings, without green spaces and with intense generation of heat from traffic, commerce and services); the meteorological conditions (the intensity of the island is at its maximum when the sky is totally clear and there is no wind, and at its minimum in those situations when there is atmospheric instability, such as wind, cloud and precipitation); and the proximity of the coastal lagoon (which borders the city to the west and northwest and moderates seasonal temperatures. The urban heat island influences the comfort and health of its inhabitants, thus urban planning is very important in the moderation and prevention of this phenomenon.

Keywords Urban heat island · Coastal city · Meteorology · Aveiro (Portugal)

Introduction

The interaction between man and the climate is global but it also manifests itself on the scale of our urban climatic habitat in the form of heat islands, which are regulated by meteorological conditions but also moderated by man's actions.

If the city creates its own climate, it also creates its own comfort or discomfort. The heat island is, more and more, an expression of man's capacity to change the environment and create, if not prevent, a grave and irreversible situation of climatic and environmental discomfort (Yamashita 1996). The urban climate, particularly the heat island, has become very important from the human environmental point of view, because of the increasing trend towards people living in urban areas.

The urban heat island is designated, generically speaking, as the urban space in which the temperature is higher than those of the surrounding rural areas. It is a complex phenomenon, which results from the various interactions between human and environmental factors and has numerous environmental, social and economic consequences (Alcoforado 1988; Bristow and Mullens 1995).

The urban heat island is caused by the distortion in the energy balance in the constructed areas resulting from the thermal behaviour of the materials used in the buildings and streets, and the alterations in the diffusion of heat introduced by the urban space and ground use. The most significant characteristics of the heat island are the intensity, which is the difference between the maximum urban temperature and the minimum rural temperature (Oke 1978, cited in Gómez 1985), and its spatial and temporal variations. These characteristics are directly related to the diverse factors that contribute to the formation of the heat island and condition it. Such factors may be natural (synoptic situation, weather, wind, topography, the presence of water surfaces) or urban (urban morphology, anthropogenic activities) (Gómez et al. 1993).

The urban heat island can determine the climatic comfort of the urban populations, affecting their health, their labour and their leisure-time activities; there are also economic effects, for example the additional cost of climate control within the buildings, and environmental effects, such as the formation of unhealthy smog in the

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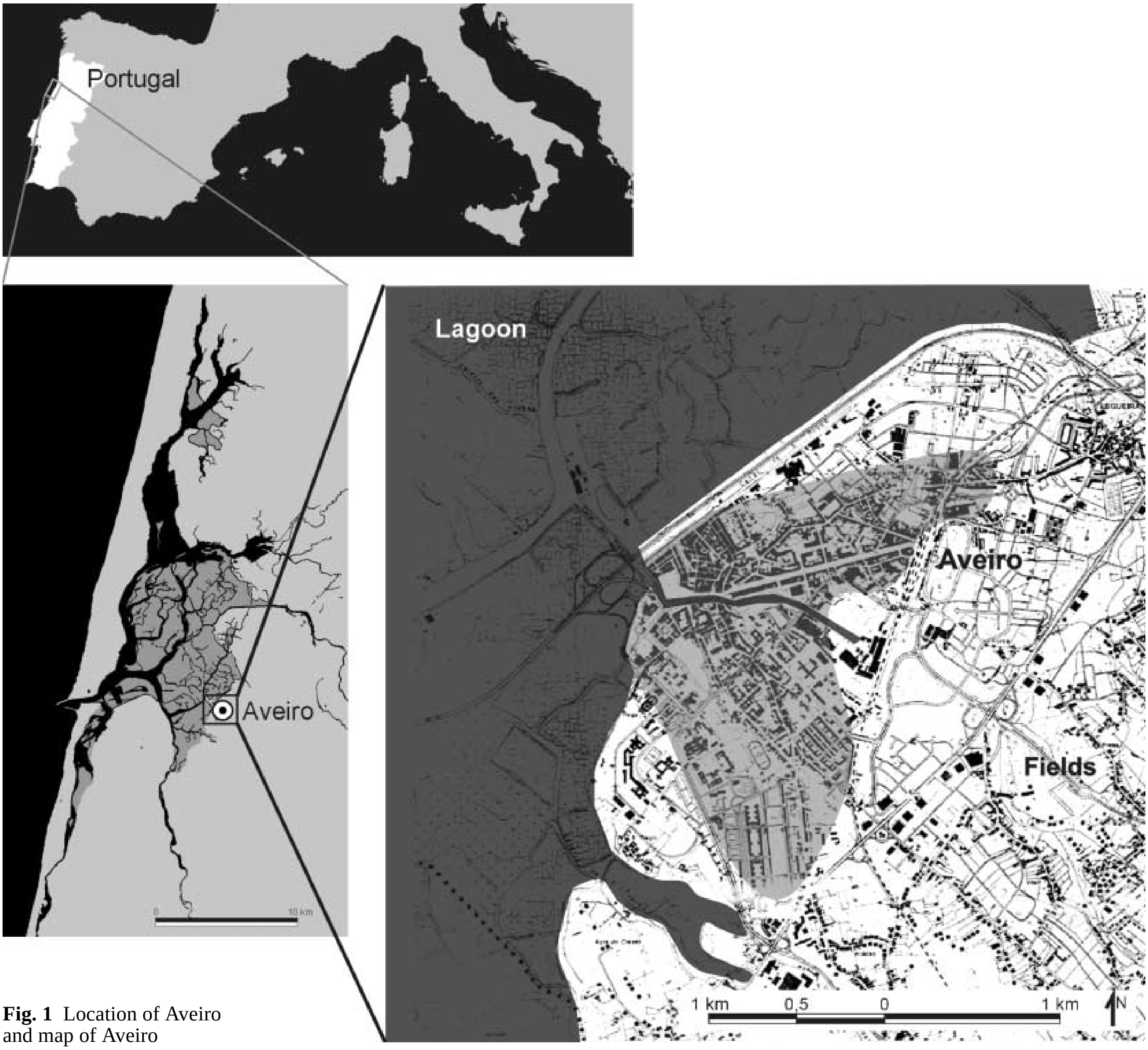

Fig. 1 Location of Aveiro and map of Aveiro

cities and the degradation of green spaces (Driscoll 1985; Myer 1991; Gómez et al. 1993).

To moderate this phenomenon it is necessary to study and understand its causes and consequences. For this reason, we have sought to identify an urban heat island in Aveiro, investigating its form and intensity and the factors that condition it. This is a pioneering study in this city, which would not be expected to have an urban heat island because of its size. Aveiro is a small coastal city in Portugal, with approximately 38 000 inhabitants. It is flat and borders 45 km of coastal lagoon (see Fig. 1). Aveiro is surrounded by marshland and salt-pit zones and rural zones. According to the Köppen classification, it presents a humid temperate climate, with a dry season and summers that are not very hot but are extensive – Cbs climatic form (Botelho 1993, unpublished report). In urban terms, the city occupies an area of approximately 6 km^2 and has an irregular form, approximately that of a V, divided by a branch of the coastal lagoon (see Fig. 1).

Materials and methods

Data sources

To determine the presence and form of the urban heat island, scheduled measurements of the air temperature (using temperature sensors: a Datataker 50 data logger properly calibrated beforehand) were taken, by passenger car, along previously defined routes, covering diverse areas of the city and its surroundings: urban spaces [the central business district (CBD), the old commercial zone, the old quarter, the habitation zone and open and garden zones], rural surrounding areas and the encircling marshland.

The measurements were taken during 48 nights in the summer, autumn and winter of 1996, between 2300 hours and 0100 hours – the time in which the differences between the urban and rural temperatures are supposedly highest (Gómez et al. 1993).

To analyse the influence of the meteorological conditions on the urban heat island, each day that scheduled measurements of the air temperature were taken, meteorological data for that day (synoptic situation, cloud cover and wind velocity) were also recorded.

Data treatment

The air temperature follows the natural daily cycle and, although its temporal variation is relatively slight, between 2300 hours and 0100 hours it can reach 1.5°C. Therefore, since the measurement of the air temperature in the various sampling sites was not simultaneous, as ideally it should be, the data obtained were later corrected with the formula:

$$T_{cor}=T + (\Delta t \cdot V)$$

where T_{cor} is the corrected air temperature in the sampling site, Δt the time lag between the start of the route and the sampling site, T is the measured air temperature in the sampling site and V the cooling velocity during the route. After correction of the data, the relative temperatures were calculated (the difference between each temperature value and the minimum value of the route) and, from these, isothermal maps were prepared.

After a numerical scale had been established for the urban structure and activities (according to the constructed surface, the height of the buildings, the soil impermeabilisation, the green spaces, the traffic, the habitation, tertiary activities), the diverse sampling sites of the route were classified and quantified. The distance to the lagoon was also measured for each sampling site, for future statistical analysis.

As well as the urban aspects, other factors that govern the heat island (synoptic situation, cloud cover and wind velocity) were also catalogued and quantified after a numerical scale had been established (as used in Alcoforado 1988).

Statistical analysis

For the correlation analysis we used the Spearman correlation coefficient (non-parametric) to detect interaction standards between:

- The relative air temperature in the diverse sampling sites of the route and the geographical characteristics of these sampling sites (urban structure and activities, distance from the lagoon)
- The intensity of the heat island and the diverse climatic variables (cloud cover, synoptic situation, wind velocity).

We also used the classification analysis (hierarchical agglomeration through complete linkage and Euclidean distances) to analyse the spatial standard of distribution of the air temperature in the city of Aveiro and its surrounding areas. This spatial standard was obtained from one matrix constituted with the different sampling sites of the route as objects and the various night measurements as descriptives. (Ludwig and Raynolds 1988).

Results

Isothermal maps

Two extreme and representative situations of Aveiro's heat island are presented here.

In Fig. 2 the isothermal map corresponds to an anticyclonic meteorological situation, where the distribution of the relative air temperature follows, very approximately, the construction density and the anthropogenic activities, in a thermal gradation: rural, peripheral areas and the city; and, within the city: open zones, habitational zones, the old quarter/commercial/CBD, with a focus on the CBD as the "peak" of the heat island. During the night the moderating effect of the marshland on the air temperature is not pronounced and the island is found centred over the city. The intensity of the urban heat island on the night in question was 7.5°C.

In Fig. 3, the isothermal map corresponds to a low-pressure meteorological situation, where the isolines are parallel to the coastal lagoon, indicating its moderating effect on the air temperature. A "current" of hot air should also be noted, originating from the lagoon and penetrating the city along its central canal. The distribution of the relative air temperatures appears to be conditioned only by the distance from the lagoon and not by the urban structures or activities. The intensity of the urban heat island on the night in question was 1.6°C.

Table 1 The Spearman correlation coefficient between the intensity of the heat island and the respective geographical variable. The average values are shown with the actual values in parentheses

Geographical variable	Correlation coefficient
Urban structure/activities	(0.43; 0.86) 0.69
Distance from the lagoon	(–0.35; –0.87) –0.54

Table 2 Spearman correlation coefficient between the intensity of the heat island and the respective meteorological variable

Meteorological variable	Correlation coefficient
Cloud cover	–0.83
Synoptic situation	–0.68
Wind velocity	–0.51

Correlation analysis

According to Table 1, we can verify the significant positive correlations (P<0.05) between the air temperature and the urban structure and activities for every night measured. We also verified the significant negative correlations (P<0.05) between the relative air temperature and the distance from the lagoon.

In relation to the meteorological variables (Table 2), we can verify significant negative correlations (P<0.05) between the intensity of the heat island and the synoptic situation and consequent cloud cover and wind velocity.

Classification analysis

In the dendrogram obtained (Fig. 4), where the different sampling sites of the city and its surrounding areas are grouped according to the similarity of their relative air temperatures, we can verify that it is possible to distinguish, only from the air temperature, different classes that faithfully correspond to different urban zones. In ad-

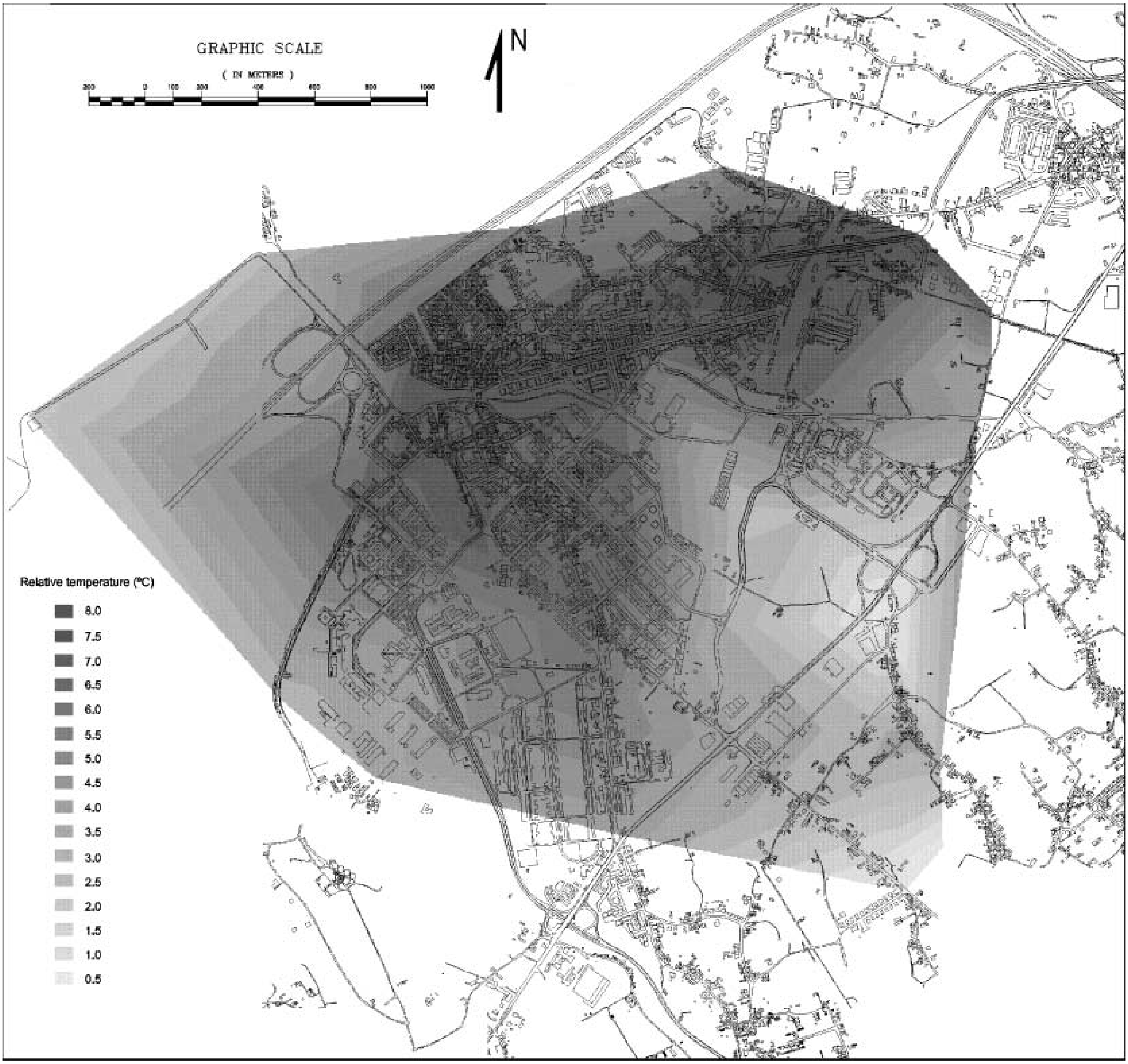

Fig. 2 Isothermal map in relation to the heat island of Aveiro; anti-cyclonic situation (1 September 1996)

dition, it is even possible to distinguish the city (old commercial areas, CBD, residential areas), the periphery (city–lagoon, city–countryside, open areas) and the rural areas (fields, rural habitation).

Discussion

By analysing the isothermal maps we can verify that the form and intensity of Aveiro's urban heat island is extremely variable, a result of the interaction between two factors: the condition of the city as an urban space with a certain morphology and activity, and the fact that the city is on the coast and therefore subject to all the meteorological characteristics that arise from its proximity to the coastal lagoon and to the Atlantic Ocean. When the first factor is prevalent, the heat island is centred over the city; when the second factor is prevalent, the island is diverted over the coastal lagoon.

The significant positive correlations ($P<0.05$) between the air temperature and the urban structure and activities reflect the effects of construction (the density and height of buildings, lack of green spaces) and of the anthropogenic activities on the intensification of the heat island.

The anthropogenic activities, such as traffic and the use of air conditioning and heating, which are great energy consumers, generate heat in the city. This heat is added to the heated urban materials during the diurnal

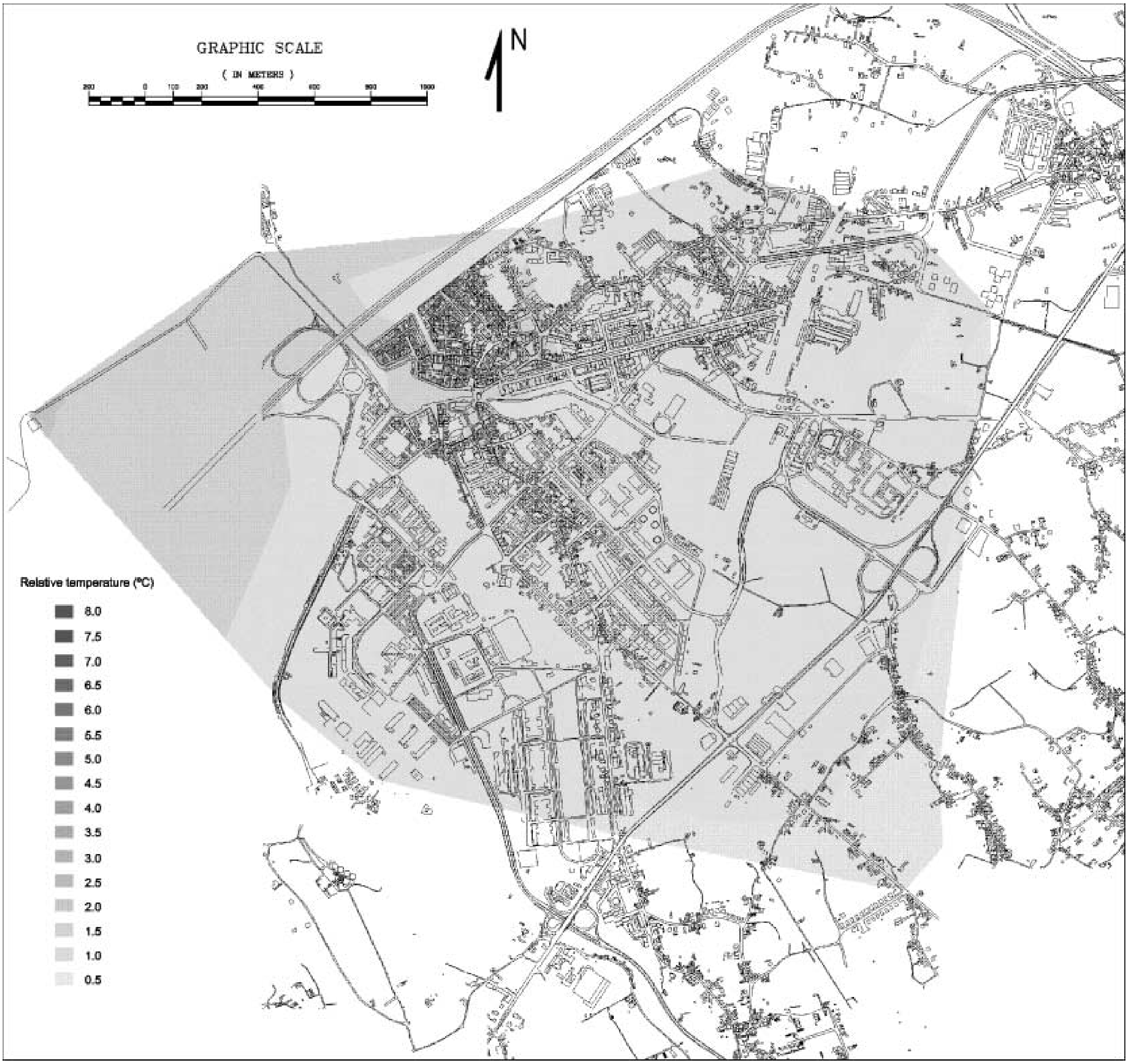

Fig. 3 Isothermal map in relation to the heat island of Aveiro; cyclonic situation (21 September 1996)

solar radiation and retained amidst the buildings through the multiple reflections between them, reducing the interface with the atmosphere. All the heat that is accumulated during the day is freed at night, preventing the night-time cooling of the urban atmosphere. The reduced green spaces and the soil impermeabilization in the built-up areas also contribute to the intensification of the heat island, because the reduced evapotranspiration means that there is minimal cooling by evaporation in the city (Alcoforado 1988; Gómez et al. 1993; Hidore and Oliver 1993).

In the dendrogram obtained the air temperatures of the city and its surrounding areas are strictly defined by the features of the different sampling sites, which confirms that the air temperature faithfully follows the urban structure and activities and is conditioned by them.

The significant negative correlations ($P<0.05$) between the relative air temperature and the distance from the lagoon confirm the important influence of this water surface and of the Atlantic Ocean in moderating the city's air temperature (Hidore and Oliver 1993).

In relation to the meteorological variables, the significant negative correlations ($P<0.05$) between the intensity of the heat island and the synoptic situation and consequent cloud cover and wind velocity confirm that weak intensities are associated with low pressure (cyclonic) or perturbation – atmospheric instability, strong winds and cloudiness, the occurrence of precipitation. The high-intensity islands correspond to high-pressure (anti-

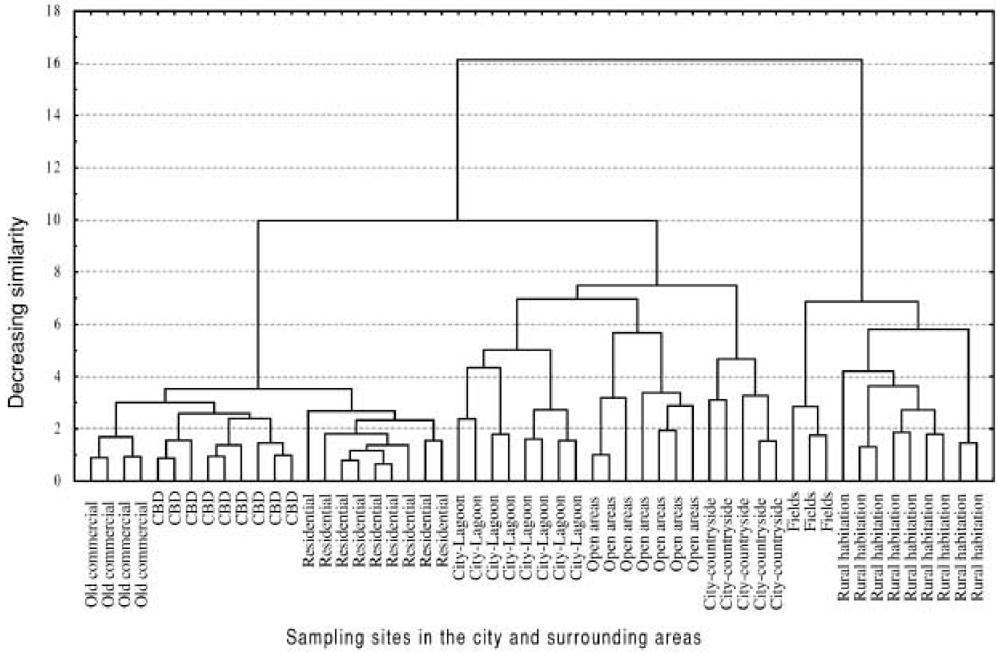

Fig. 4 Classification dendrogram binding sampling sites of the city and its surroundings, according to the similarity of their relative air temperatures

cyclonic) situations – clear sky and no wind. Similarly, the more extensive the cloud cover and the higher the wind speed, the smaller the intensity of the heat island.

The absence of wind or small breezes prevents the dispersal of the freed urban heat, which increases the intensity of the heat island; on the other hand, if the wind blows, the turbulence removes the heat from the city and, consequently, the temperature variations between this and the rural surroundings are smaller. The clouds reduce the reception and release of radiation, moderating the urban heat island (Hidore and Oliver 1993).

Conclusion

With this study, we were able to verify that the city of Aveiro, although small, does present its own urban climate and heat island, the intensity of which (the difference between the maximum urban temperature and the minimum rural temperature) can reach 7.5°C. The heat island is essentially conditioned by three factors: the urban morphology, the meteorological conditions and the proximity to the coastal lagoon and to the Atlantic Ocean.

The more extensive the construction, the traffic and the lack of green spaces, the greater is the intensity of the heat island. The anti-cyclonic conditions of clear sky and calm weather accentuate the heat island and its correspondence with the urban morphology. On the other hand, the cyclonic conditions lessen the intensity of the heat island and divert it to the lagoon.

The effects of this heat island in Aveiro on the comfort and health of its inhabitants should be the object of a future study. For now, we draw attention to the need to prevent this phenomenon. Urban planning should take account of the construction density, the distribution and impact of the heat emissions and the importance of green spaces so as to reduce the development of uncomfortable, polluting and costly urban heat islands.

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