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The use of thermography to highlight the relationship between air and surface temperatures in urban scenes

The use of thermography to highlight the relationship between air and surface temperatures in urban scenes

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Abstract. The correlation between air and surface temperatures is recurrently used as a descriptor of the urban climate within built environments. The aim of this paper is to explore the possibilities of time-lapse thermography to visualize this relationship in time and space. To this end, thermograms are colorized using a relative-to-air temperature scale, instead of the usual absolute one. This approach was tested for two deep urban canyons belonging to cities with different climates. Relative-to-air thermography has two main advantages: it facilitates comparisons between the thermal responses of urban scenes under different climates and makes convective energy exchanges more comprehensive.

1. Introduction

Despite substantial advances in the scientific understanding of urban climates made in the last three decades, the implementation of climate-sensitive design strategies in urban planning is still limited in practice [1,2]. In this regard, the development of graphical tools could be helpful to allow translation of research findings into urban design guidelines for different climates.

Understanding the mechanisms driving urban surface temperatures is required for a climate-conscious urban design, since this parameter directly affects human comfort [3] and city energy consumption [4]. The study of urban surface temperatures poses, though, considerable challenges mainly due to the remarkable variations of this parameter in both time and space. Time-lapse thermography, a technique which allows spatializing thermal information and tracking it through time, has proven to be useful in this regard, first from nadiral [5] and more recently from oblique and perspective views [6–8].

The temperature of a surface expresses the result of the energy balance taking place between a solid element and its surrounding atmosphere. Consequently, surface and air temperatures will be related somehow, in a way that does not appear in classical thermography, which displays absolute temperatures [9,10].

The aim of this paper is to explore the use of *relative-to-air thermograms* as a graphical tool for analysis of the built environment's thermal response. This work seeks to investigate the possibilities of this original approach of thermography to help in understanding the relationship between the characteristics of a certain urban environment and the energy exchanges taking place within them.

2. Method

The proposed approach was tested on two urban canyons belonging to cities with different climates (Figure 1): *Rejas de Don Gome street* in Córdoba (Spain, 37.9° N) and *Tonneliers street* in Bayonne (France, 43.5° N). These streets are geometrically similar (average cross-section W/H≃0.5, bounded by almost North & South facing facades) but different from a material point of view, particularly regarding their façades. In general, Cordoba facades are lighter coloured, less perforated and heavier constructed than the ones in Bayonne.

Within the two selected urban canyons, a measurement campaign was carried out during a sunny day with virtually no wind, seeking to maximise the air-to-surface thermal differences. A FLIR B200 infrared camera was placed aligned to the street axis with a 10° tilt to the horizontal, so that the street was globally framed under a perspective view [7]. Visible and infrared images were shot every half-an-hour in both environments. At the same position, air temperature and relative humidity were acquired at 1-meter-height every 5 minutes by means of a HOBO- U12 thermo-hygrometer. For interpretation purposes, data on two additional environmental parameters were collected: wind speed at a 2-meter-height and global horizontal irradiance at the closest weather station to the experimental site.

The collected thermographic data were post-processed to generate a set of thermal images. First, raw thermograms were calibrated for a unitary emissivity (ε=1) and a null distance (d=0m). That is, assuming that all the objects in the scene behave as black bodies and the attenuation caused by the atmosphere existing between them and the camera can be neglected. Under these conditions, temperatures were deduced directly from the radiant flux received by the camera [11]. Within deep urban canyons, the authors showed that the deviation in temperature between perspective and frontal thermography was lower than 2°C [8].

Second, by means of an image post-processing routine in MATLAB, thermal images composing the sequence were registered in 2D and segmented in two regions: built surfaces and sky. Apparent temperatures of this later region were corrected to take into account the reduced longwave emission of the atmosphere within the spectral range of measurement of the camera, following [11].

Finally, a sequence of “relative” thermograms was generated for each street. That is, a time-lapse of images colorized according to the differential of temperature between surface and air at the time of the shot. Using a colorbar comprising two opposite gradients, surfaces warmer than the air are distinguished from those colder than air, depicting also the intensity of this phenomenon. Based on these graphical outputs, the thermal response of the urban canyons was analysed from a qualitative-quantitative point of view, discussing the potentials and limitations of absolute and relative colorbars.

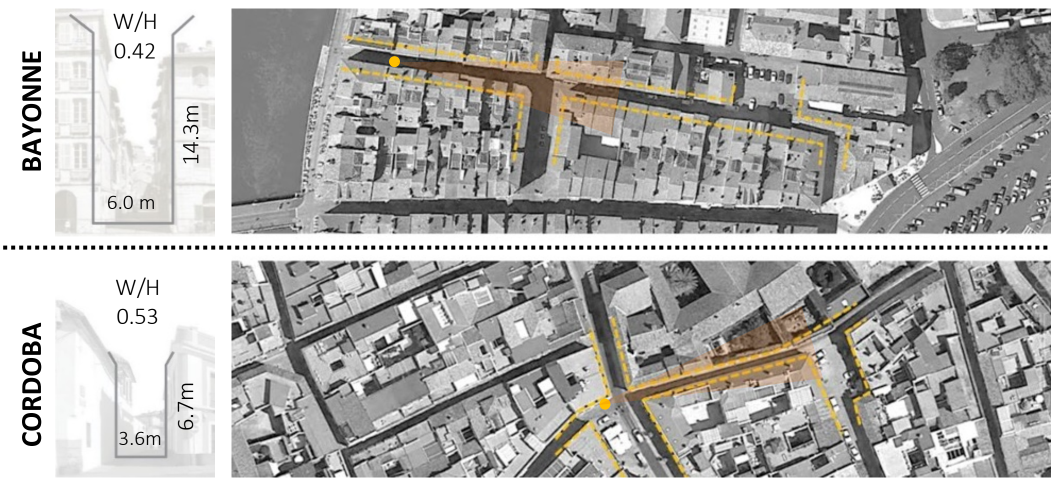

Figure 1. Average cross section and aerial view of *Tonneliers street* in Bayonne (up) and *Rejas de Don Gome street* in Cordoba (down).

3. Results & discussion

3.1. Background weather

The experimental data presented here were collected in Bayonne and Cordoba on 23 April and 25 July 2017, respectively. According to solar radiation data (Figure 2), the studied days were completely cloudless and similar in terms of daytime duration (14 hours, approximately). The difference in global irradiance received by an unobstructed horizontal surface between the cases was lower than 100 W/m^2. Higher differences are expectable, though, in the radiation impinging on the actual urban canyon surfaces, as a result of the variation in sun elevation and consequently, in the shadows cast by the built environment.

Atmospheric conditions at street level during the measurement days corresponded to the normal ones for the time of the year at each location (Figure 2). During the Bayonne campaign, the air temperature ranged between 9 and 20°C, usual values for sunny spring days in this region. As for Cordoba, measurements took place during a hot and dry summer day, with air temperatures between 26 and 39°C.

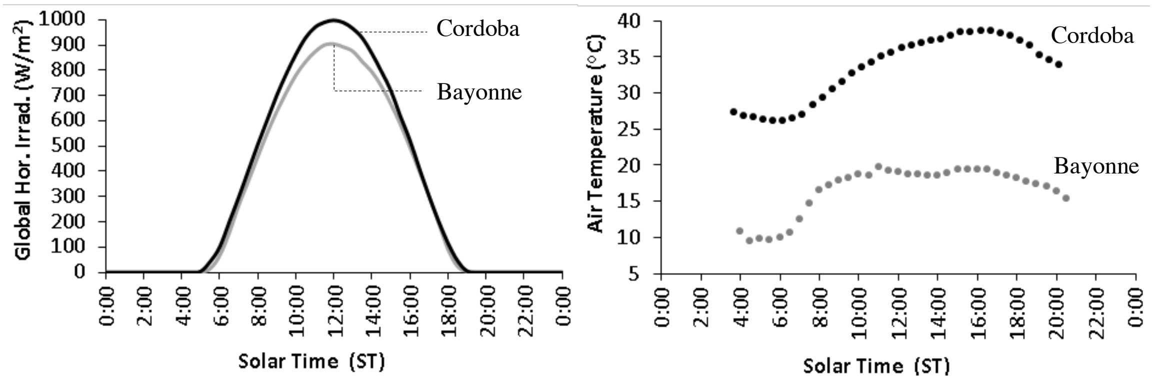

Figure 2. Global horizontal irradiance (left) and air temperature (right) during the measurement campaigns in Bayonne (23/04/2017) and Cordoba (25/07/2017).

3.2. Sequences of thermograms with an absolute scale of temperatures

After processing the experimental data, a sequence of photographs and "absolute" thermograms was generated for each location. Figure 3 depicts an example of the graphical outputs obtained, corresponding to the shot at 14:00 ST, the time of the day with the highest surface temperatures. To be able to describe the range of absolute temperatures exhibited by each urban scene, colorbar limits were settled between 2 and 36°C for the thermogram sequence of Bayonne, and between 22 and 56°C, for the one of Cordoba (Figure 3, middle).

By analyzing each of these thermal sequences separately, it is possible to understand thermal processes taking place at each individual location. However, conclusions drawn from comparing these two sequences may be misleading, since colorbar ranges are different. To overcome this limitation, thermograms could be colorized using a common scale - between 2 and 56°C - for both urban scenes (Figure 3, right). Direct comparisons are now possible, yet this representation hinders the observation of thermal details on individual scenes. Under these conditions, observations can hardly go beyond identifying the warmest and coolest environment (Cordoba and Bayonne, respectively), information which gives no revealing insights on the mechanisms driving the differences in the thermal responses of these environments.

Despite the thermal differences in absolute terms between the two case studies, results show that surface temperatures are correlated to air temperatures in both urban environments. This fact becomes evident when the intra-daily range of air and surface temperatures are displayed simultaneously, as done in the middle of Figure 3 (dash line on the thermogram colorbars). This finding highlights, the interest of visualizing temperatures of an urban scene in relative terms to that of the air as a "normalization" strategy to visually compare thermal scenes.

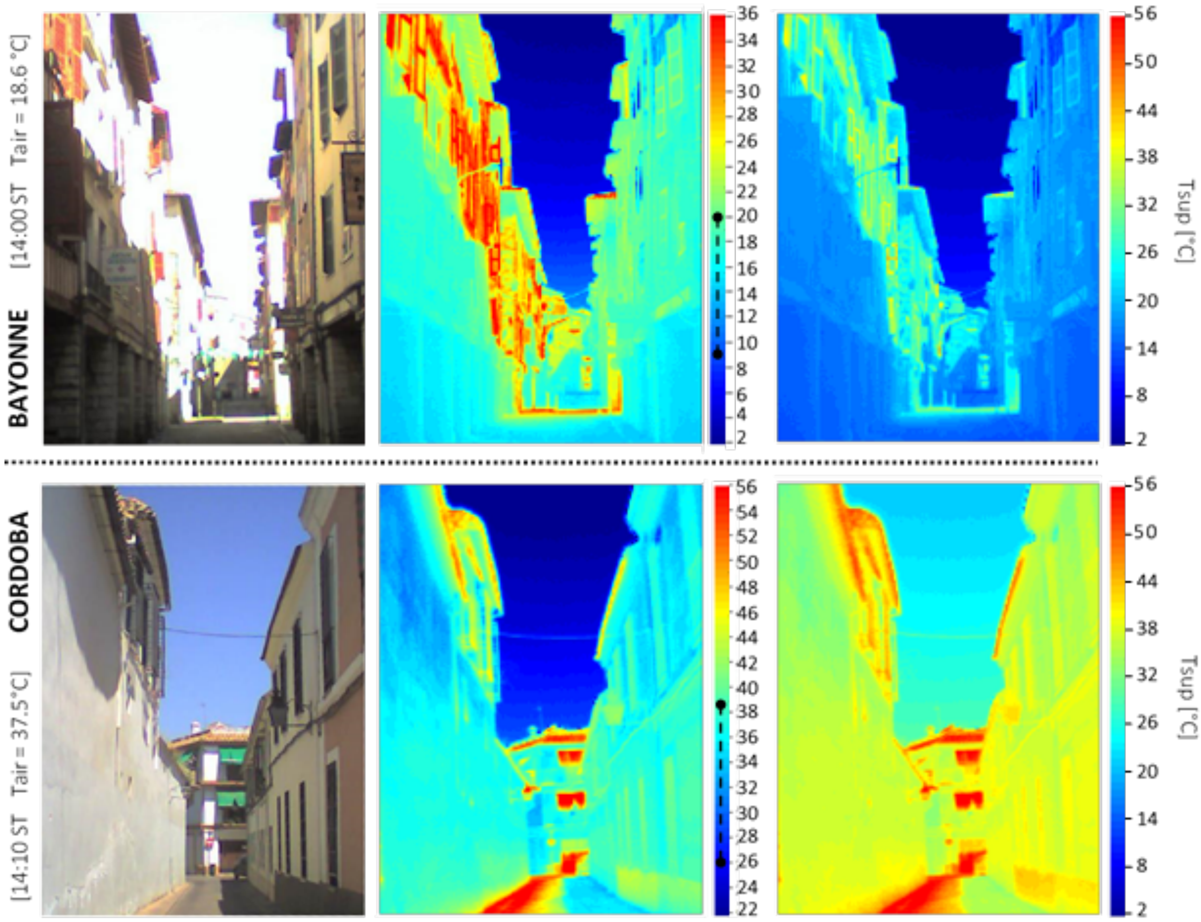

Figure 3. Photograph (left), thermograms with individual (middle) and common (right) colorbar of *Tonneliers street* in Bayonne (up) and *Rejas de Don Gome street* in Cordoba (down).

3.3. Sequences of thermograms with a relative-to-air scale of temperatures

For each urban scene, a sequence of relative-to-air thermograms was generated defining a maximum differential of ± 20°C to the air temperature. Figure 4 depicts an extract of these time-lapses comprising three representative times of the day (04:00, 14:00 and 20:00).

Results show that before dawn, built surfaces of both urban scenes presented temperatures close to air, with differences not exceeding ± 5°C, and a quite symmetrical thermal distribution on both sides of the street (Figure 4, left). At this moment, most of the built surfaces in Bayonne street were at the same temperature or slightly warmer than the air, whereas, in Cordoba, the upper half of building facades is slightly colder than it. Leaving aside the streetlights, the warmest surfaces correspond to those with low sky view factor (like the arcades of Bayonne street) and/or those surfaces with high inertia and solar absorption (sidewalk on the bottom of the south façade in Cordoba). During the daytime, surfaces exposed to solar radiation heat up, also increasing their differential to the air. Two hours after midday, surface temperature may exceed in up to 20°C the one of the air (Figure 4, middle). In the Bayonne case, the solar patch matches almost perfectly the warmest area of the urban scene, whereas, in Cordoba, this is only perceptible on the street pavement. This relative representation allows for visualizing the thermal impact of multi-reflexions regarding the overheating of surfaces compared to the air. This effect is present in the Cordoba street, a highly reflective urban environment, where dark surfaces of the North façade are significantly warmer than the air, despite being in shadow. Finally, after the sunset, urban surfaces exhibit the smallest thermal differences to the air (Figure 4, right).

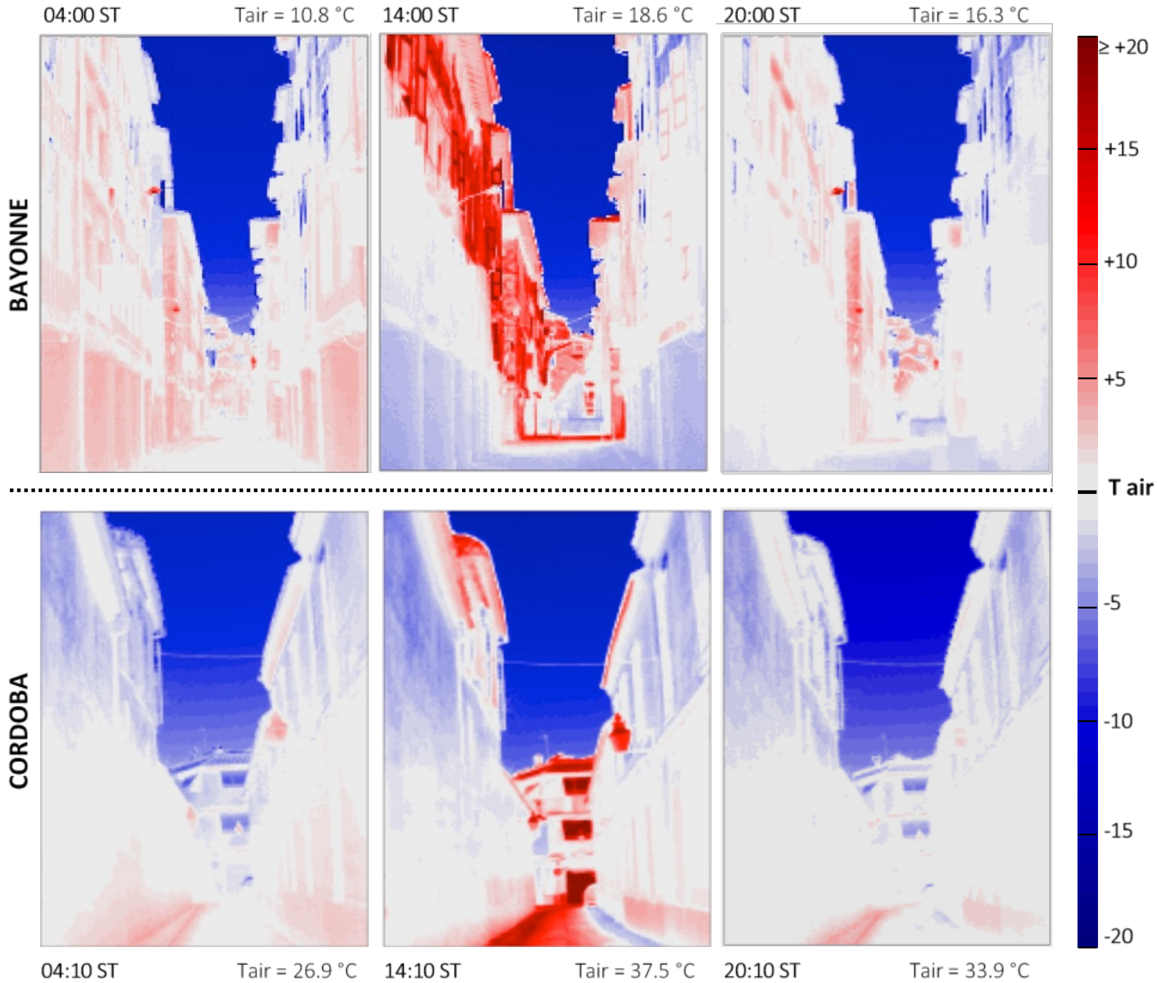

Figure 4. Extract of the sequence of thermograms with a relative-to-air temperature scale for *Tonneliers street* in Bayonne (up) and *Rejas de Don Gome street* in Cordoba (down).

The difference between surface and air temperatures is one of the two factors influencing convection fluxes over surfaces [$Q_{conv} = h_c.(T_{sup}-T_{air})$]. Hence, relative-to-air thermography may also be used to make more comprehensive convection exchanges within the canyon. This kind of graphical representation provides spatialized information about the "direction" of the heat flux by convection at each point (red colored areas in Figure 4 would be losing energy by convection, whereas the blue colored ones would be gaining it). The color gradients may also give some insights on the variation in "intensity" of the phenomenon, even though the magnitude of Q_{conv} is strongly dependent on h_c (affected by several factors including wind conditions and geometrical and material properties of surfaces [12]). Additionally, depicting differences between air and surface temperature helps to understand how natural convection works in a certain urban environment, a key part of total convective exchanges under calm wind conditions (as was the case of the days investigated here). Results of our study cases show the remarkable spatial heterogeneity of convection fluxes within a complex built environment, contrary to common assumptions in building energy simulation programs [12].

For this study, a single value of air temperature – the one measured 1 meter above the ground level– is used as a reference to generate relative thermograms. Since air temperature varies in space within urban environments, this fact should be taken into account when interpreting the results of this work. Intra-urban variations in air temperature are, nonetheless, substantially smaller than the ones exhibited by surfaces [2]. In this regard, Santamouris et al. found that, in deep urban canyons such as the ones studied, air temperature stratification was not significant, rarely exceeding 2-3°C [13]. Taking this into account, the colorbar has been designed with a broad central band in white in order to avoid changes in color due to the errors in the estimation of air temperature. Because of this, limited changes are expected on the thermal trends discussed here.

4. Conclusions

Based on the results of this work, two main contributions of *relative-to-air thermography* have been evidenced compared to *traditional thermography*, where surface temperatures are expressed in absolute terms.

First, this system of representation facilitates the comparison of thermal responses among urban scenes under different weather conditions. Since surface temperatures may significantly differ in absolute terms among different urban environments, it is not always possible to draw relevant conclusions from comparative analysis based on using *traditional thermography*. By fixing the air temperature as a reference for thermograms, more generalizable design-related observations can be made on the thermal performance of built environments. In this vein, the results of this work highlighted the key role of reflectivity - at both local and street scale - on the overheating of surfaces compared to the air.

Second, *relative-to-air thermography* provides additional insights about the spatial variation of convective fluxes within built environments, making evident their direction over the surfaces of a complex urban scene. *Relative thermography* evidences the remarkable variation of heat fluxes and convective exchanges within the built environment, where a single building may be losing energy through some parts while, at the same time, gaining it through some others.

The findings of this work demonstrate that the information obtained from infrared sequences can be significantly enriched by carrying out an additional graphical post-processing, beyond the usual functionalities of IRT commercial software. This paper highlights the interest of spatializing energy fluxes and correlating them with urban surface properties to overcome the gap between climatic knowledge and urban intervention.

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