Title: ASSESSING THE COOLING EFFECT OF URBAN TEXTILE SHADING DEVICES THROUGH TIME-LAPSE THERMOGRAPHY

Keywords: *Urban shading; Sun sails; Thermography; Heat mitigation; Street surface temperature*

Abstract: The overheating of the street surfaces has negative impacts on pedestrian comfort and cooling energy consumption. During the past few decades, extensive research has been carried out on heat mitigation technologies. However, there is limited knowledge on the efficacy of textile solar protections at the urban scale. In this paper, we investigate the cooling potential of sun sails on urban surfaces based on field measurements carried out in several streets of Cordoba (Spain). To this end, we develop a novel method based on time-lapse thermography at street level that allows for assessing the thermal behavior of urban scenes, in a comprehensive and agile way. Results show that high-mounted sun sails have a global cooling effect over the street, regardless of its orientation. Decreases due to sun sails in ground temperature reach up to 16°C, and in façade temperature, up to 6°C. Our observations demonstrate that sun sails can provide a heat mitigation efficacy similar to standard technologies while entailing softer levels of intervention.

1. Introduction

The understanding of the mechanisms that drive urban surface temperature is crucial for sustainable urban planning. Surface overheating has negative impacts on human comfort and city energy consumption [1]. As global warming progresses, heat mitigation has become a top priority for urban planners [2–4]. During the past few decades, intense research has been carried out regarding the efficacy of the different cooling technologies [5,6], and numerous projects have been implemented to cool cities [7,8]. Both simulations and experimental studies have demonstrated that one of the most effective strategies to avoid surface overheating is shading [6,7]. At the urban scale, there are three main ways to achieve this goal: occluded urban morphologies, vegetation, and artificial shading devices. The existing literature mainly focuses on the effects of self-shading urban geometries [9–11] and shade trees [12–14]. In contrast, the attention given to artificial solar protections has been far more limited [15].

Textile shading devices are an attractive option when the use of vegetation is restricted, removable solar protections are advisable, or a flexible geometrical design is needed [16]. Mediterranean cities, typically facing these constraints, provide a traditional example of the use of textile solar protections [2,17]. These devices usually consist of a set of sun sails placed as a canopy at different heights within the street canyon (Figure 1).

Fig. 1. Spanish streets with textile canopy shadings known as 'toldos' in (from left to right): Trapería St (Murcia, 1905), Sierpes St. (Sevilla, 1918), Preciados St. and Arenal St. (Madrid, 2018).

The most evident effect of sun sails is a reduction in the solar radiation penetrating the urban canyon. However, the installation of these devices modifies the street microclimate in other ways, involving changes not only in the radiative fluxes but also in the air temperature and wind flow within the canyon. All these processes affect the energy balance of urban surfaces, and thus their temperature. Up to now, investigations about sun sails have mainly focused on pedestrian comfort [6,15,18–20], leaving their effects on the urban surfaces almost unexplored. This paper aims at filling this gap from an experimental approach by collecting field data on the surface temperature within streets sheltered by sun sails.

Measuring surface temperatures within urban canyons constitutes a complex task due to the remarkable variations of this parameter in both time and space [1]. The presence of sun sails over the street brings new research challenges from the methodological point of view. To date, the two most common techniques for measuring surface temperatures at the street scale are [5,21]: contact thermometers [11] and aerial infrared thermography, whether from aircraft [22] or elevated platforms [23]. Both approaches have shortcomings for a comprehensive evaluation of sun sail effects, which requires visualizing the distribution of surface temperatures over all the street facets and the solar sails simultaneously, at different times of the day.

The main goal of this work is to assess the potential of sun sails to limit the overheating of street surfaces. We conducted field measurements in four streets of Cordoba (Spain), a Mediterranean city with severe summer conditions, and a long tradition in the use of urban sun sails. To this end, we developed a novel method based on time-lapse thermography at the street level. Infrared images are shot in perspective to frame all the street surfaces in a single picture and repeated several times a day to create a sequence [24]. Measurements took place in streets with two orientations, sheltered by sun sails with different tissue properties. Based on the comparison of results among the cases, we provide guidelines for the installation of street sun sails.

2. Case study description

2.1. City context

Cordoba is a mid-sized city located in the south of Spain (37°N). Its historical center has a compact morphology, with deep and intricate street canyons bounded by buildings of unequal heights. The configuration of this urban fabric dates from the Medieval Muslim period of the city and constitutes one of the tourist attractions of the city.

Cordoba has a temperate Mediterranean climate, with mild winters and hot and dry summers (Csa, according to Köppen's classification). Long-term records for the region are available from the airport meteorological station, located at a semi-rural location 6 km away from the city center (Table 1). According to this data, mean monthly temperatures (T_{air}) range between 9.3°C in January to 28.0°C in July and August. The annual precipitation level in Cordoba is low, and the number of cloudless days (SD), high, especially in summer. Air temperatures during this season are especially high, with average maximums ($T_{air\ MAX}$) ranging from 31°C to 37°C between June and September. Peaks on air temperatures over 40°C and heat waves are recurrent in these months. Normal wind conditions on the outskirts of Cordoba are light breezes, lower than 3 m/s on average [25]. Due to urban obstructions, episodes with no wind are frequent within the city, especially at the bottom of deep urban canyons. These severe climatic conditions represent a source of discomfort not only for the citizens but also for tourist visitors, limiting the number and intensity of activities held outdoors in the summertime.

Table 1. Cordoba Climate (Source: data between 1981-2005 at the Airport – AEMET Service) [25]

	Tair MAX (ºC)	Tair (ºC)	Tair MIN (ºC)	RH (%)	SD	I (h)
Jan	14,9	9,3	3,6	76	10,3	174
Feb	17,4	11,1	4,9	71	8,8	186
Mar	21,3	14,4	7,4	64	8,5	218
Apr	22,8	16,0	9,3	60	5,8	235
May	27,4	20,0	12,6	55	7,3	288
Jun	32,8	24,7	16,5	48	13,7	323
Jul	36,9	28,0	19,0	41	20,9	363
Aug	36,5	28,0	19,4	43	19	336
Sep	31,6	24,2	16,9	52	10,3	248
Oct	25,1	19,1	13,0	66	7,8	204
Nov	19,1	13,5	7,8	73	8,4	180
Dec	15,3	10,4	5,5	79	8,1	148
YEAR	25,1	18,2	11,4	60	130,5	2903

2.1. Urban area sheltered by textile shading devices

As a heat mitigation strategy, every year since 2002, the local government and a local commerce association install urban canopy shadings over several commercial streets. The shading devices remain installed between May and October, which represents almost a third of the year. The extent of the urban area sheltered by sunshades was 2.980 m^2 in 2018, but there is an extension project ongoing (Figure 2). Today, there are urban sun sails in four streets (Figure 2): *Jesus y Maria* St, *Cruz Conde* St, *Gondomar* St, and *Concepcion* St. The first two are limited by buildings facing East and West (yellow). The last two, by buildings facing North and South (blue). From now on, we will refer to these as EW streets and NS streets, respectively.

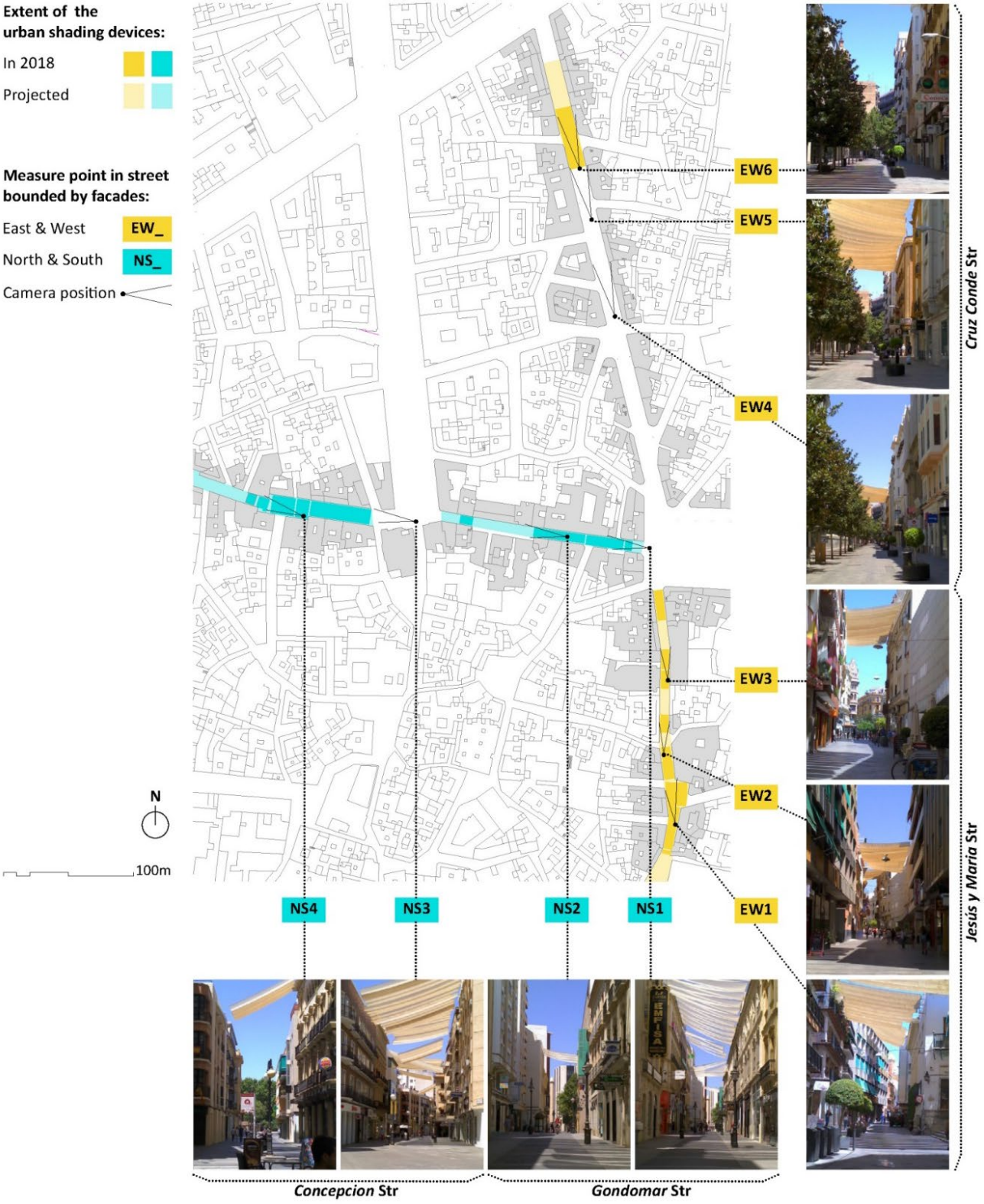

Fig. 2. Urban area sheltered by canopy shading devices in Cordoba, and location of the measurement points for the experimental campaign

The selected streets are deep urban canyons with an average aspect ratio ranging between 1.30 and 1.82. Figure 3 depicts stereographic views from the middle of these streets, including solar obstructions due to both buildings (grey) and shading devices (yellow and blue). In the EW streets (yellow), urban canopy shadings help to block sunrays impinging on the ground during the central hours of the day all year long. Conversely, in the NS ones (blue), these devices block the solar radiation reaching the ground almost all day long for several months around the solstice.

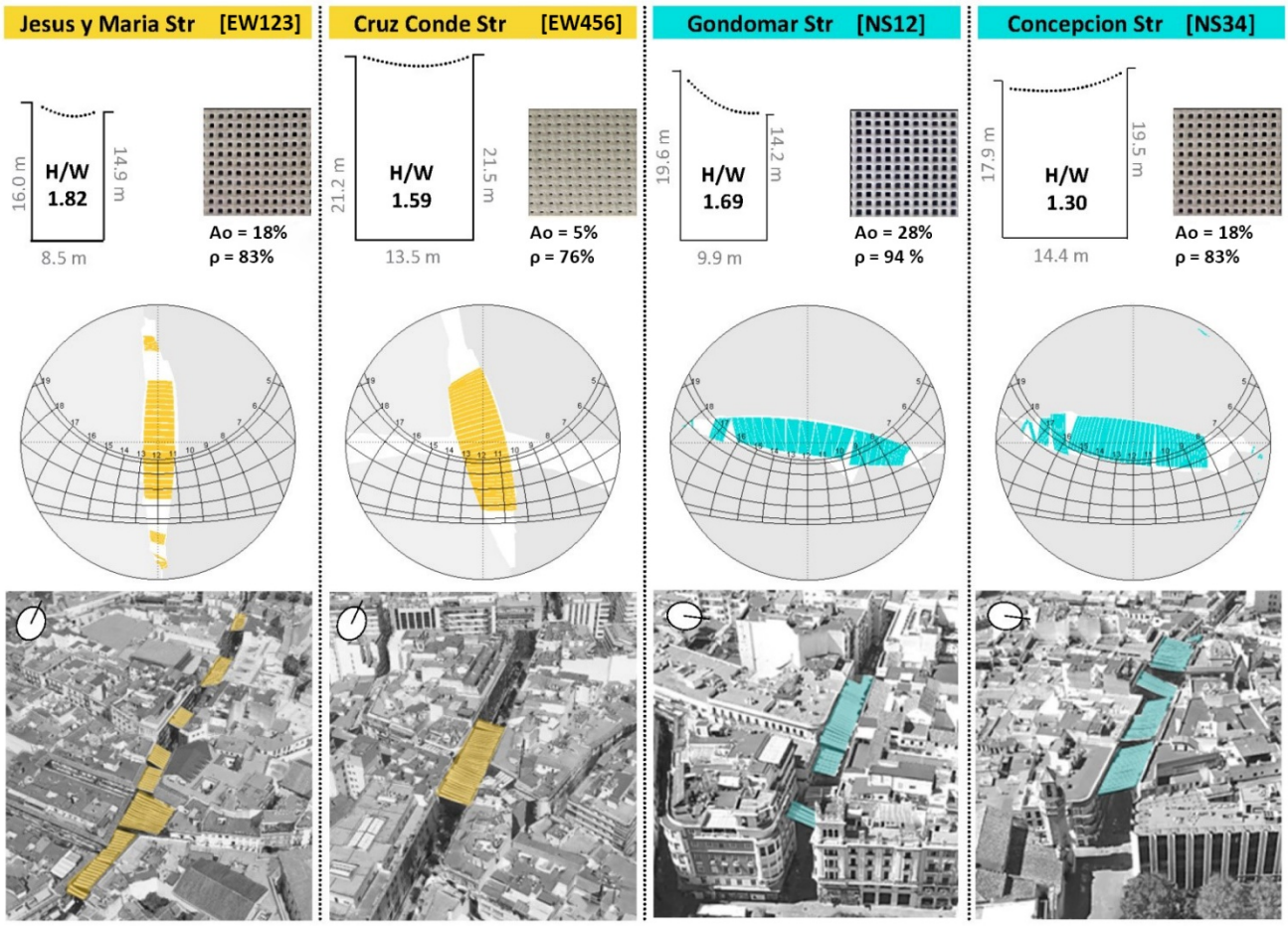

Fig. 3. Description of the streets under assessment (from top to bottom): average section, tissue properties, stereographic view from the middle of the street, perspective aerial view.

In Cordoba's city center, all the shading devices are placed on the upper part of the canyon, fixed to façades through metallic cables with tensors [26]. They consist of a set of rectangular or triangular pieces of microperforated polyester tissue with an exterior coating of PVC. The length of sails varies to adapt to the street width, while their width is standard (130 and 260 cm for the rectangular and triangular ones, respectively). The minimum distance between two adjacent pieces is 20cm, and between them and the façade plane, 80 cm. This spatial layout and the micro-perforated nature of the

tissue allows for diminishing the “sail effect” caused by the wind. This configuration also reduces the stagnation of warm air underneath the shading device, released through the top of the canyon by buoyancy.

The properties of textile shading devices differ among the four streets. Figure 3 summarizes their main features. Textile meshes in this urban area present three openness factors (A_o): 5%, 18% and 28%. This parameter plays a key role in textile solar protections since it correlates to the direct normal transmittance of the tissue [27]. Originally white, sun sails presented different hue colors at the time of the measurement campaign, depending on their time of use. This color change in the tissues affects their reflectance (ρ), ranging between 76% and 94%.

3. Methods

3.1. On site measurements

To assess the thermal effects of urban canopy shadings, we carried out a measurement campaign in the zone of Cordoba center sheltered by this kind of device. The core of the experimental work consisted of the shot of a set of visible and infrared images. We conceived this fieldwork to comply with two conditions. First, the work should be feasible counting on limited human and technical resources, corresponding to typical conditions in the pre-diagnosis stage of urban projects. In our case, this stands for: a person operating one commercial thermal camera for one day. The second condition was that a single campaign should be enough to cover all the studied area.

To this end, we defined ten measurement points distributed along the four street canyons under assessment (Figure 2). Three criteria guided the location choice: the distance between the measurement points, the representativeness of the framed scene, and the feasibility of the measurement. At each selected location, we placed a FLIR T460 infrared camera (240x320px, FOV=19°x25°) aligned to the street axis with a 10° tilt to the horizontal. This camera position allows for providing a global view of the street, simultaneously framing both facades of the canyon, the pavement, and a fraction of the sky partially blocked by the sun sails. To ensure the repeatability of the shot, we mark the exact position of the camera tripod at each measurement point, as explained in [24].

We carried out measurements nine times a day, visiting the selected locations in the same order (from EW1 to NS4). The measurement times were distributed throughout the day to provide a representative view of the thermal behavior of street surfaces throughout the daily cycle. The first round took place one hour before dawn, seeking for a quasi-steady state of street surfaces. The last one, two hours after sunset to capture the effects of inertia. The rest of the rounds were scheduled symmetrically around midday, with smaller intervals in the central hours of the day. Since measurement rounds lasted approximately 40 minutes, each round started 20 minutes before the target hour to minimize the deviation between it and the actual measurement time.

Additionally, we collected data on several environmental parameters for the calibration of thermographies and the interpretation of results. The air temperature and the humidity were registered at the pedestrian level using a HOBO thermo-hygrometer. The wind speed was measured with a TESTO i405 hot-wire anemometer at a 2.2-meter height over the street pavement. Global horizontal irradiances (LW and SW) were retrieved from the closest weather station to the experimental site, located at the Cordoba airport.

3.2. Image post-processing

To obtain graphical material for thermal analysis, we undertook several post-processing tasks on the raw thermographies.

First, we calibrated thermographies using the commercial software of the thermal camera (FlirTools+). Air temperature and relative humidity were set to the values recorded during the measurement campaign at the time of each shot. For all the thermographies, the object emissivity was fixed at one and its distance to the camera at zero. Under these conditions, all the objects in the scene are considered black bodies, and the atmosphere is assumed to be completely transparent to the infrared radiation [28]. Thus, the observed temperatures correspond to the "apparent temperatures" deduced directly from the total radiant power reaching the lens in the camera spectral range (7–13 μm).

Second, the thermal and visible images taken at each measurement point were registered using automatic intensity-based algorithms (Matlab routine). These images were cropped to the same size to ensure the coherence of the sequence. Though this operation inevitably results in information loss, it can be limited if the camera position is carefully marked. (Notice that the images in this work contain between 93 and 98% of pixels of the raw images). Then, thermal images at each measurement point were 'stacked' in chronological order to generate an n-dimension matrix (*multidimensional array*) that allows for reading the thermal dataset in time and space.

Finally, we use this thermal dataset to generate the graphical material for analysis. On the one hand, sequences of thermal images with color scales adapted to the phenomena under study. On the other, graphs on the temperature evolution at a certain point of interest.

3.1. Urban modeling and complementary solar analysis

To help to understand the experimental results, we carried out complementary solar analyses on a 3D model of the studied urban area. Buildings were modeled by extrusion of the footprints from the cadastral plans, using the information about buildings height gathered from Google Earth Pro. Sun sails were modeled as individual planar surfaces with variable tilt and dimension. The number of pieces and their position were defined according to the technical paper developed by the city council [26].

Using the software *Heliodon 2*, we developed two kinds of solar analyses: i) solar exposure studies at certain points of interest based on solar stereographic diagrams; ii) computations of the solar radiation received by urban surfaces through the complete warm season in Cordoba. Notice that *Heliodon 2* computes the solar flux just taking into account the direct component of solar radiation and assuming clear sky conditions [29].

4. Results and discussion

4.1. Weather conditions

Results of the measurements presented here correspond to 8 July 2018, a typical summer day in Cordoba, with a clear sky and warm air temperatures (Figure 4). Air temperatures (T_a) within the four studied streets ranged between 23.7°C (at 06:30h) and 36.5°C (at 17:30h). Minimum air temperatures were similar in the four canyons. Maximum air temperatures, however, exhibited higher differences. The shallowest canyon (Concepcion St) registered the highest air temperatures. Conversely, the narrowest and the most sheltered one (Jesus y Maria St) had the lowest maximum temperatures.

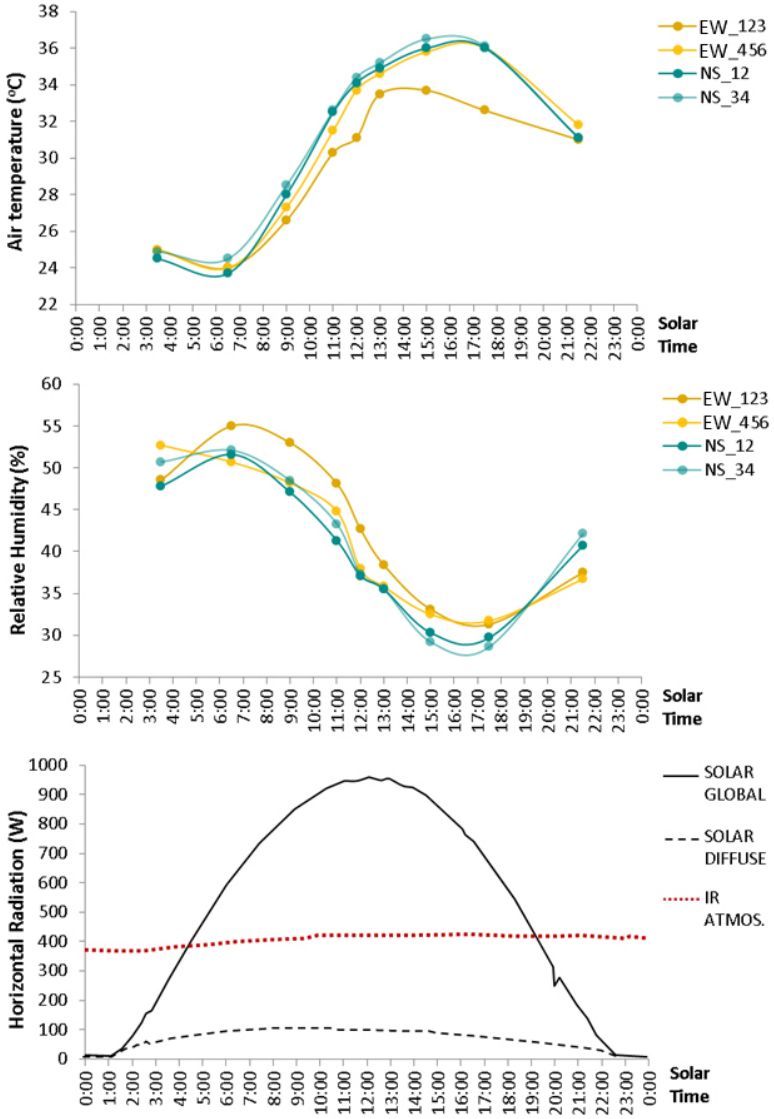

Fig. 4. Air temperature (up) and relative humidity (middle) within the streets under assessment; Solar and infrared horizontal radiation at Cordoba Airport (down).

196 Atmospheric conditions during the measurement day were dry and calm, which facilitates the
197 thermography interpretation. Relative humidity (RH) in the measurement sites varied between 29%
198 and 55% during the investigated period, with a daily pattern evolving inversely to that of T_a. At the
199 bottom part of the urban canyons, the average wind speed oscillated between 0.1 m/s and 1.6 m/s,
200 remaining most of the times below 1 m/s, a reference value expressed in the literature for
201 thermographic analysis [30].

202 Figure 4 depicts the horizontal short and longwave radiation measured at the Airport weather station
203 on the day of the experimental campaign. These values may be a good approximation of the ones in
204 the study area, given the clear weather conditions and the proximity between these two locations.
205 Solar radiation data corresponded to a typical summer day for the region, with a clear sky and high
206 radiation. The horizontal shortwave global irradiance reached 950 W/m^2 during the central hours of
207 the day, mostly due to direct solar radiation. As for longwave radiation, the sky vault sent an average
208 flux of 400 W/m^2.

209 *4.2. Temporal and spatial evolution of the sun sails shadows depending on street orientation.*

210 Sun sails unevenly affect the street thermal environment depending on street orientation. To illustrate
211 differences in this regard, Figure 5 presents an excerpt from the image sequence obtained in two
212 perpendicular streets: *Jesus y Maria* St (EW façades) and *Gondomar* St (NS façades).

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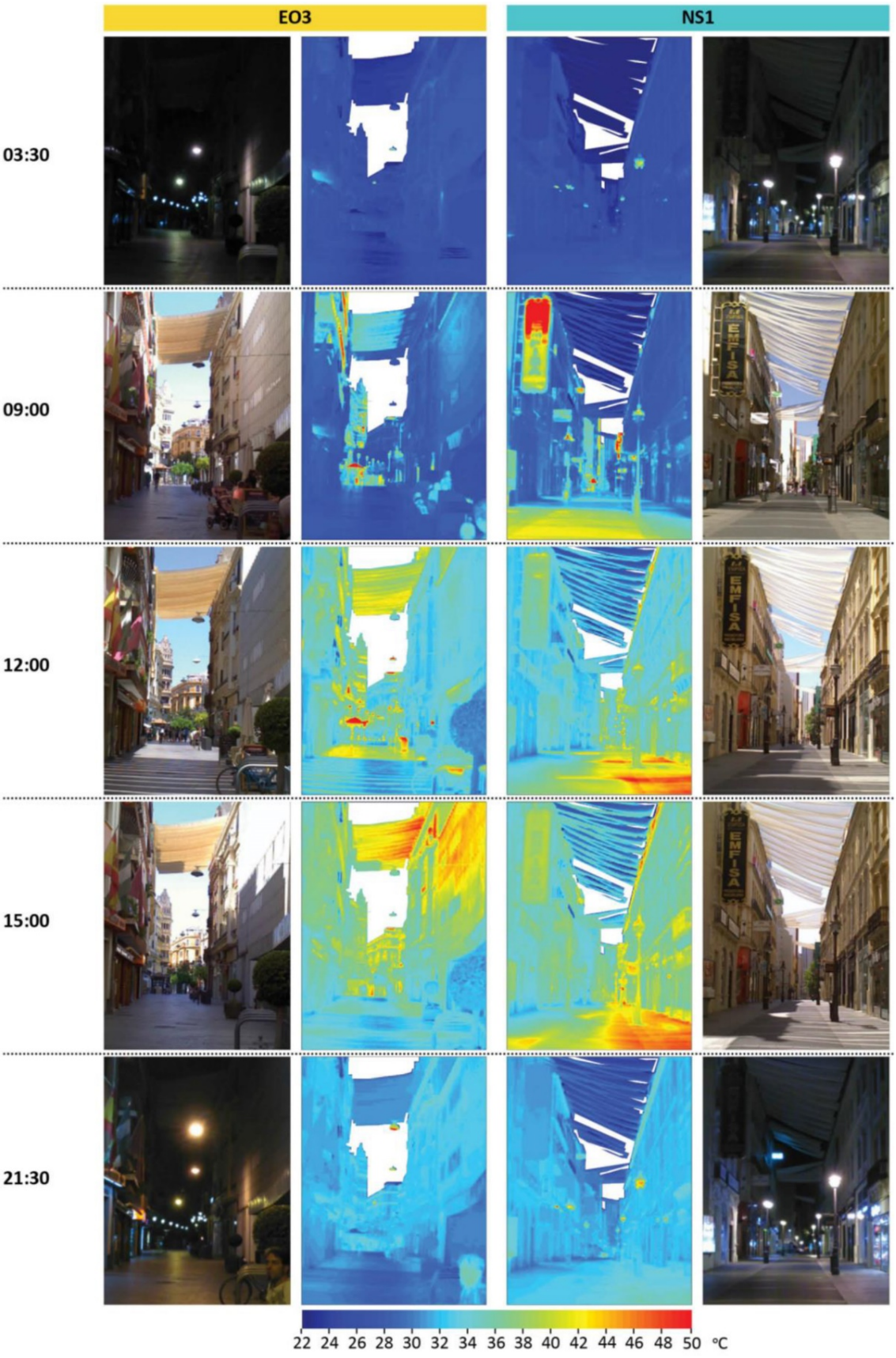

Fig. 5. Excerpt from the visible and infrared time-lapses in Jesus y Maria St (scene EW3, on the left) and Gondomar St (scene NS1, on the right).

Results show that, before dawn, surface temperatures were quite homogeneous and close to the air in both urban canyons. At 03:30 ST, temperatures of built surfaces in all the studied urban scenes ranged between 24°C and 29°C, for air temperatures between 24.5°C and 25.0°C. At this time, thermal differences due to the presence of the shading device were small and, consequently, hardly visible when using the suitable color bar for studying the entire day (between 22 and 50°C). Still, it is possible to see that the areas of pavement and façade covered by sun sails in *Gondomar* St were slightly warmer than those with a higher sky view (up to 2°C).

After sunrise, the thermal differences among the urban scenes become more evident, due to the uneven solar energy distribution over urban surfaces between orientations. In the same vein, the effects of sun sails are more remarkable during the daytime, generating shaded areas that remain colder than the adjacent sunlit ones. The location and size of these areas depend on the street orientation and the time of the day.

During the early hours of summer days, sun sails within streets bounded by East-West façades (such as *Jesus y Maria* St) cast their shadow over the upper part of the East façades. Throughout the morning, the shaded area grows towards the bottom of the canyon, reaching the street pavement only for some hours around noon. At midday, sun sails shade the façade areas below them completely. As the afternoon goes by, the shaded area over the West façade decreases bottom-up. The image time-lapse shows that the shadow of sun sails in streets with East-West façades only affects surfaces placed right below it. Consequently, installing sun sails in these streets allows for creating a 'street section' that remains shaded all day long by either the buildings or the sun sails.

Within streets limited by North-South facing façades (such as *Gondomar* St), sun sails shadows present a more dynamic behavior, being able to affect surfaces located far away from the shading device. During the first and last hours of summer days, sun rays penetrate through the ends of the streets, impinging tangentially to both facades (light-colored), and more perpendicularly to the ground (darkly paved). For much of the day (i.e., images at 12:00 and 15:00), sun sails cast shadows on the South façade and the pavement area close to it. All-day long, the cooling effect in this street is more

243 significant over the pavement (darker and receiving more radiation) than over façades (more reflective
244 and less irradiated.

245 Finally, after sunset, surfaces begin to cool down, gradually approaching the air temperature
246 regardless of the street orientation. At 09:30 ST, roughly two hours after sunset, differences between
247 air and built surface temperatures in the studied urban scenes were less than 6°C (between T_a+3.6
248 and T_a-5.4°C). The pavement area closer to the base of the South façade of *Gondomar* St, and the
249 upper part of the *Jesus y Maria* St West façade, were the warmest areas of the studied urban canyons,
250 reflecting the inertial effects on surfaces sunlit some hours before.

251 The thermography time-lapses show that sun sails are an effective heat mitigation strategy for both
252 street orientations. However, the surfaces most affected by this cooling effect differ between the
253 cases. Within streets limited by North-South façades, sun sails are especially useful in reducing the
254 ground overheating for much of the day. This effect may be highly beneficial for pedestrian comfort.
255 On the contrary, sun sails over streets perpendicularly oriented are particularly helpful in shading the
256 upper part of street façades in the morning and afternoon. These solar and thermal loads are critical
257 regarding indoor comfort and cooling energy demand. Consequently, sun sails installed in this
258 orientation are especially beneficial for building users, especially those in the higher floors, as
259 investigated in [31].

260 Figures 6 and 7 depict the average solar radiation received over the ground and façades of *Jesus y*
261 *Maria* St and *Gondomar* St between 15 May and 15 September, with and without sun sails. According
262 to simulations, radiation patterns for this period are similar to the ones obtained for the measurement
263 day (8 July). Therefore, remarks about the spatial effects of sun sails in this work are essentially valid
264 for the complete warm season in Cordoba.

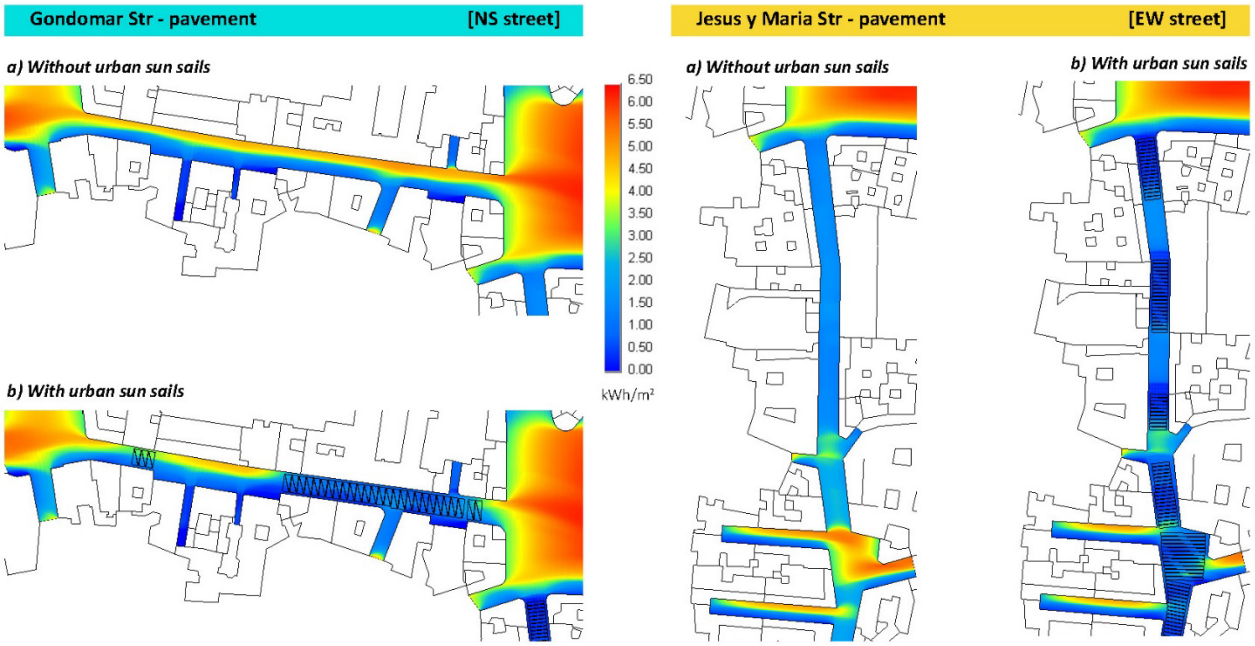

Fig. 6. Direct solar radiation impinging over the pavement of Gondomar St (left) and Jesus y Maria St (right) between 15 May and 15 September, with and without urban canopy shadings.

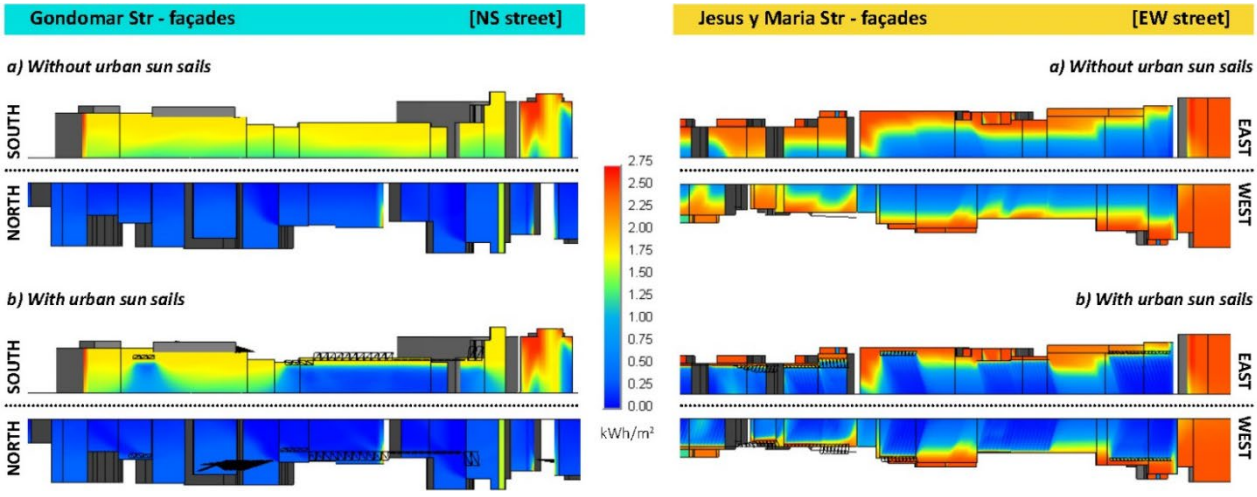

Fig. 7. Direct solar radiation impinging over the façades of Gondomar St (left) and Jesus y Maria St (right) between 15 May and 15 September, with and without opaque sun sails.

4.3. Impact of urban sunshades over urban canyon surface temperatures.

This section analyzes the impact of urban sun sails on the temperatures of the main street surfaces: pavement and façades. Results show that the reduction in surface temperature due to sun sails is more significant over the former than the latter. The overlap of two different factors explains this behavior. First, horizontal surfaces are the ones receiving the maximal irradiance during summer (up to 950 W/m^2). Second, in the investigated urban scenes, ground surfaces are generally darker than façades, hence having a higher solar absorptance on average.

To investigate the cooling effect of sun sails over the ground, we selected three regions of interest on the pavement with different levels of solar exposure (Figure 8): at the street intersections (a), within the street but not shaded by sun sails (b), within the street and shaded by them all day long (c).

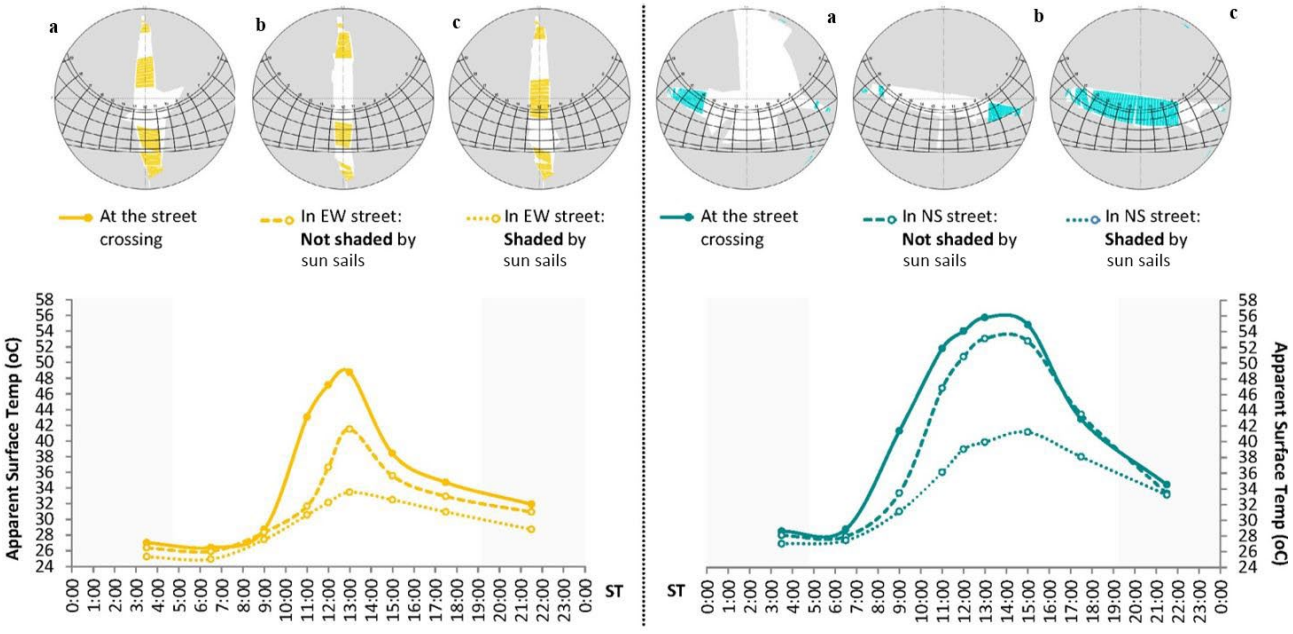

Fig. 8. Stereographic diagrams and apparent surface temperature of pavement areas in NS and EW streets (blue and yellow, respectively) with different levels of solar exposure (a,b,c).

The results show that the pavement zones shaded by the urban sun sails (c) were cooler than the other two situations assessed (a & b) all day long and for both street orientations. The cooling effect of sun sails over the pavement was maximal one hour after midday (moment of maximum horizontal irradiance). The differences between the cases gradually decreased throughout the afternoon, but they were still perceptible at the early hours of the day (up to 1.8°C until 06:30 ST). These results indicate that the cooling effect of sun sails over the pavement was more noticeable and lasted longer

in the NS streets (up to 15.9°C) than in the EW ones (up to 13.2°C). Notice, though, that the pavement area receiving direct solar radiation in NS streets consists of a 'strip' close to the South façades, whose width depends on the street aspect ratio. Therefore, sun sail benefits over the ground may affect a small area or even disappear in deep NS streets. On the contrary, these benefits will exist on the pavement of EW streets regardless of their aspect ratio, but lasting for a short period in deep canyons.

Unlike the ground, façades in this urban area are quite heterogeneous. This diversity in the optical and thermal properties of surfaces leads to significant temperature differences between adjacent zones of the same façade. Generally, the sun sail cooling potential over façades will be higher on those with high solar absorptance and highly irradiated. Within the urban context, these latter correspond to the less obstructed parts of East and West façades. Therefore, we focus the discussion about the sun sail cooling potential over façades on an EW street (*Jesus y Maria* St). We studied in further detail the four-story building indicated in Figure 9. The choice of this building is of especial interest since it has an almost homogeneous façade made of concrete slabs (α=0.5; ε= 0.90), half-sheltered by sun sails.

Fig. 9. Points of interest building for the study of the sun sail thermal effect over façades (dashed line).

Figure 10 depicts the evolution of surface temperatures throughout the day in two adjacent regions of the façade with the same area: 'b' is sheltered by sun sails, and 'a' is exposed to the sky and receiving direct solar radiation during the afternoon.

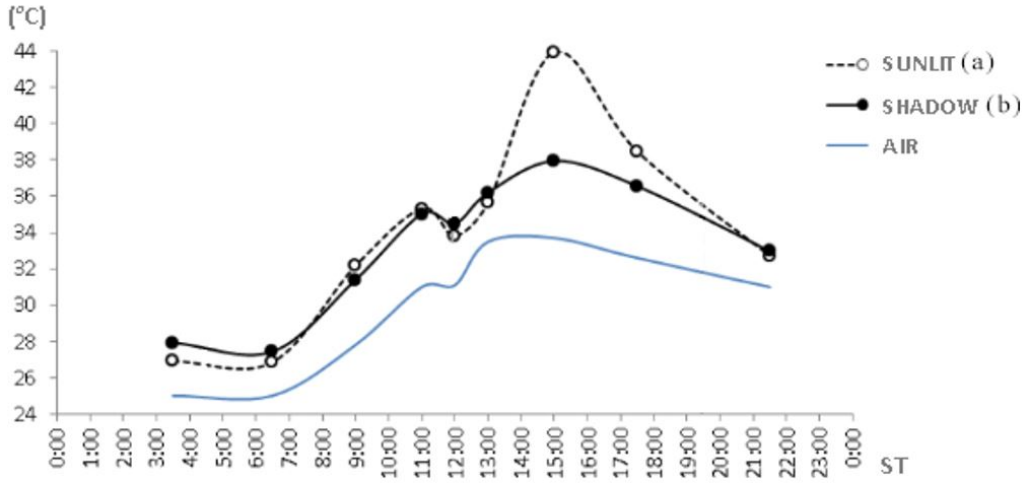

Fig. 10. Comparison between the surface temperature of a shaded (b) and sunlit (a) region of a West façade in Jesus y Maria St.

The results show that both regions registered the highest temperatures around 15:00 ST, the time of the day when the facade was receiving the maximum of direct radiation. At that moment, the sunlit region (a) was 6°C warmer than the one shaded by sun sails (b). The thermography in Figure 9 shows a similar cooling effect over all the façade area shaded by sun sails. Additionally, this thermal image evidences that sun sails heat up to some extent, becoming a new heat source for street surfaces.

During the rest of the day, thermal differences between the regions 'a' and 'b' were more limited. Façade areas under the shading device were slightly warmer than the ones outside it at several times of the measurement day. The maximal differential in this sense occurred at dawn when the sheltered region was 1°C warmer than the exposed one.

4.4. Influence of tissue features on the street thermal environment

In this section, we compare the thermal behavior of *Gondomar* St and *Concepcion* St to address the impact of the sun sail features on the street thermal environment. The selected streets are geometrically similar in terms of orientation and cross-section. However, they differ in the characteristics of the urban solar protections, being lighter-colored and more perforated in *Gondomar* St than in *Concepcion* St (Figure 3). Results show that the differences in the optical properties of the tissues resulted in temperature differences between the urban scenes, concerning both built surfaces and sun sails.

To analyze the influence of tissue properties on surface temperature, we focused on the ground of both streets. To this end, we compared the surface temperatures in three pavement zones with the same finishing (granite slabs: ρ=0.2 and ε=0.96) but different shade conditions (Figure 11).

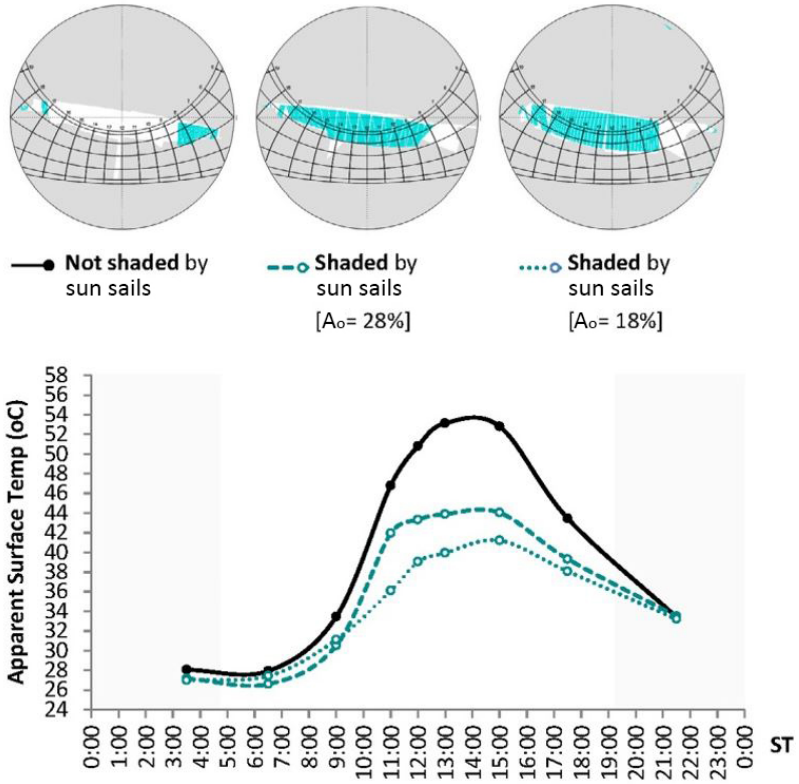

Fig. 11. Surface temperature of pavement areas: sunlit vs shaded by sun sails with different openness factors (A_o).

These results show that the two pavement zones protected by the urban shading devices remained cooler than the one not shaded by them. However, the intensity of this cooling effect differed between the streets: up to -13.2°C in Concepcion St, up to -9.2°C in Gondomar St. The difference in tissue openness may explain this variation: the higher the openness of the tissue is, the lower the cooling potential of the sun sail. This correlation, though, seems to be not linear since increasing the openness factor by 10% points reduced the cooling effect by 30%. This behavior may be due to the influence of this parameter not only on the solar radiation directly impinging on street surfaces but also by reflection. These findings highlight the key role of tissue openness since relatively small changes in this parameter result in significant temperature variations. Thought the tissue openness should be as low as possible to maximize sun sail benefits, an excessively low value of this parameter can generate an unpleasant 'indoor sensation'. Paolini et al. [18] suggest a minimum openness of 10% to avoid this effect.

Finally, we analyze the influence of the tissue reflectance on the temperature of the shading devices themselves. To this end, we compare the thermal behavior of the sun sails installed in *Gondomar* St and *Concepcion St* (Figure 12). Graphs in Figure 13 correspond to the average apparent temperatures of the image region corresponding to sun sails in the thermography time-lapses shot in these streets.

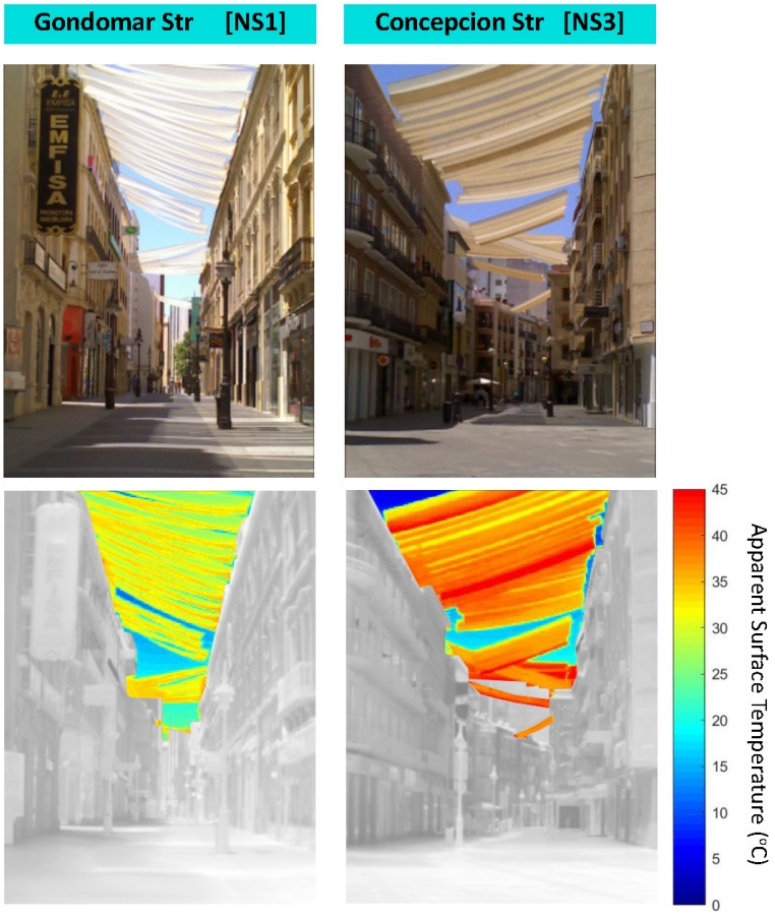

Fig. 12. Photography and thermography of sun sails with different reflectance in: Gondomar St (ρ=94%) and Concepcion St (ρ=83%) at 12:00.

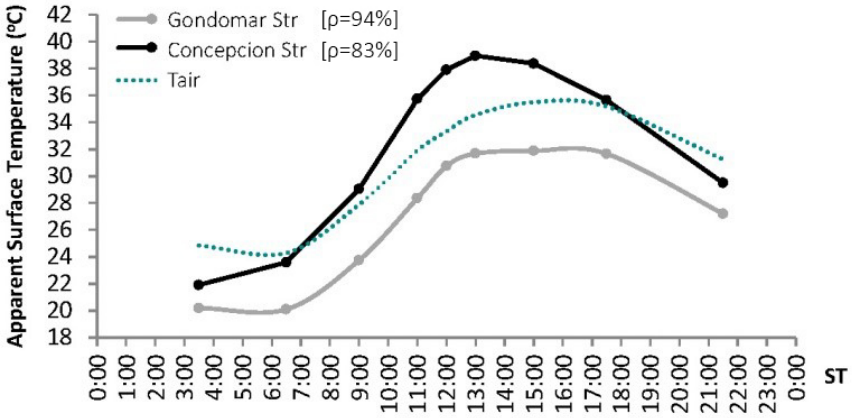

Fig. 13. Average apparent surface temperatures of sun sails with different reflectance in: Gondomar St (ρ=94%) and Concepcion St (ρ=83%) at 12:00.

357 During the measurement campaign, sun sails in Concepcion St were warmer than in Gondomar St,
358 with differences ranging between 1.7°C and 7.4°C. This behavior seems to correlate to the difference
359 in the tissue reflectance between the two cases: the higher the reflectance of the tissue, the lower its
360 apparent temperature. Notice that a relatively small difference in the tissue reflectance (11 %points)
361 led to a significant change in its apparent temperature (up to 7.4°C).

362 Textile shading devices are thin and lightweight elements with a low thermal capacity. Consequently,
363 their heat storage is almost negligible, and convective and radiative fluxes will mainly drive their
364 surface temperature. Under clear sky conditions, sun sails will be substantially warmer than the sky
365 vault regardless of the tissue color (Figure 12). When made of light-colored tissues, sun sails
366 temperatures remain similar to the surrounding air all day long (Figure 13). Low-reflective tissues, in
367 contrast, may significantly overheat, becoming an additional heat source for pedestrian and built
368 surfaces. Longwave exchanges with shading devices may have a noticeable impact on urban comfort
369 [19] and cooling demand [32]. Therefore, to maximize benefits from sun sails on human comfort and
370 energy consumption, tissues with high reflectance and low transmittance are preferable.

5. Discussion

Results show that sun sails allow for significant reductions in the daytime temperatures of urban surfaces. This cooling is due to the prime benefit of these devices: a reduction in the shortwave radiation absorbed by street surfaces. Sun sails have, though, some adverse effects on the street microclimate that partially offset the temperature lowering achieved due to shading:

- A reduction in the radiative cooling of urban surfaces towards the sky. Our results show that, due to this effect, surfaces below sun sails are slightly warmer during the night than those adjacent but more exposed to the sky (up to 2°C). This rise in temperature, though small, might have some impact on the quality of outdoor and indoor climates. In this regard, Evins et al. [32] showed that small changes in the outside building temperature (+2°C, on average) could significantly affect building cooling demands (+19%). Further investigations are required to assess the convenience of installing night-removable shading devices.
- A reduction of the wind speed within the canyon. In the investigated case study, the use of sun sails seems to have a minor impact on wind speed, since wind conditions in Cordoba are already calm without these devices. As sun sails overheat when sunlit, they could foster an upward movement of warm air that could partially counterbalance the absence of wind. Given the crucial role of wind speed for urban comfort and thermal building performance, it would be advisable case-by-case analyses in this regard.

Onsite observations are invaluable since only they represent the real complexity of the problem under investigation. Besides, measurements provide useful insights and data to compare with simulations models, that could extend their usefulness [1]. Our experimental data are in good agreement with simulations in [18], which show temperature decreases over the pavement of up to 12°C for a street in Milan with similar climatic and material conditions to the ones in Cordoba. In contrast, we found significant differences when comparing to other theoretical works, such as [6]. This work found higher decreases in surface temperature due to the use of sun sails (up to 27°C on the pavement), despite considering a less opaque tissue. The discrepancies between the simulated and measured studies highlight the need for field data on the cooling potential of sun sails in real urban environments.

6. Conclusions

This paper presents an empirical study on the impact of urban sun sails on street surface temperatures. The work relies on the results of a thermographic campaign conducted in four streets of the historical center of Cordoba sheltered by these devices. Based on the field observations, we draw the following conclusions about:

- **The potential of sun sails as heat mitigation strategy at a street scale.** During the day, the use of sun sails significantly limited the overheating of the urban surfaces, especially of the dark and highly irradiated ones. Thus, the most intense cooling effect of sun sails in this case study occurred over the pavement, reducing its temperature up to 16^{o}C. The decrease in façade temperatures was also noticeable, reaching 6°C on walls with a mid-reflectance. These results demonstrate that sun sails allow for a surface temperature lowering similar to standard mitigation technologies (e.g., cool coatings [33,34]), while entailing softer levels of intervention on the built environment. During the night, surfaces below sun sails were slightly warmer than those more exposed to the sky (<2°C). Future works should assess the benefits of installing removable-devices to counteract this effect.
- **Guidelines for the installation of street sun sails.** Installing high-mounted devices is crucial to ensure that sun sails have a global cooling effect over the street. Sun sails should have the lowest possible solar transmittance and the highest possible reflectance to maximize their benefits. Thus, the tissue openness should be as low as possible (though not below 10% to avoid an 'indoor sensation'). In our case study, an increase in the tissue openness of 10 points (from 18% to 28%) reduced the cooling effect of sun sails by 30% (from -13.2°C to -9.2°C). Also, light-colored tissues are preferable to limit sun sail overheating. Sun sails are highly effective in reducing surface temperature regardless of street orientation. In streets with Nord-South façades, sun sails are especially beneficial in lowering pavement temperatures,

crucial for pedestrian comfort. In those with East-West façades, the main benefits of sun sails concern the building façades, thus building users.

- **The potential of perspective time-lapse thermography for microclimate studies.** Street-based thermography has only been used occasionally in urban climate research, thus, a major contribution of this work was to the advancement of the observational technique. The use of perspective views demonstrated to be an agile way for acquiring a global thermal information at street scale, even counting on limited resources (one person, one camera, one day).

To our knowledge, this study is the first experimental work about the potential of sun sails as a heat mitigation technology relying on street-based thermography. In this sense, our observations contribute to a better understanding of urban climate in two ways: from the methodological point of view, by presenting a novel approach that might help to address the gap in microclimate data at the street level; and, from a climate-conscious design perspective, by highlighting sun sails as a highly effective soft intervention.

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