



HAL
open science

Comparison of cooling grey solutions in the sense-city urban demonstrator for adapting cities to heat waves

Anne Ruas, Valentin Clemence, Bruno Barroca, Yan Ulanowski

► To cite this version:

Anne Ruas, Valentin Clemence, Bruno Barroca, Yan Ulanowski. Comparison of cooling grey solutions in the sense-city urban demonstrator for adapting cities to heat waves. *Urban Climate*, 2024, 55, <10.1016/j.uclim.2024.101874>. <hal-05139371>

HAL Id: hal-05139371

<https://hal.science/hal-05139371v1>

Submitted on 2 Jul 2025

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire HAL, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



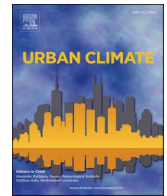
Distributed under a Creative Commons CC BY-NC 4.0 - Attribution - Non-commercial use - International License



ELSEVIER

Contents lists available at [ScienceDirect](https://www.sciencedirect.com)

Urban Climate

journal homepage: www.elsevier.com/locate/uclim

Comparison of cooling grey solutions in the sense-city urban demonstrator for adapting cities to heat waves

Anne Ruas^{a,*}, Valentin Clemence^a, Bruno Barroca^b, Yan Ulanowski^b

^a IMSE/COSYS Laboratory, Université Gustave Eiffel, 14-20 bld Newton F-77420, Champs-Sur-Marne, France

^b Lab'Urba, Université Gustave Eiffel, 14-20 bld Newton F-77420, Champs-Sur-Marne, France

ARTICLE INFO

Keywords:

Heat waves
City adaptation
Cooling devices
Canyon street
Sense-city

ABSTRACT

Summary: Faced with the increase in urban heat in summer, cities must quickly adapt by offering cool islands. If nature-based solutions are efficient and popular, other so-called grey solutions exist and can also provide solutions. In this paper we compare standard grey solutions in Sense-city, an urban demonstrator equipped with sensor, located in the scientific campus of Cité Descartes at Marne la Vallée. Our objective is on the one hand to compare the effectiveness of standard solutions over time, but also to study the ability of sense-city and its canyon street to study this phenomenon despite its relatively small size.

Methods: In this work we follow an experimental approach using a wide coverage of calibrated sensors deployed in Sense-city. We have conducted two measurement campaigns in July 2021 and July–August 2022 where we study the effectiveness of standard solutions (shading, white floor surface, street watering) to reduce the air temperature in the canyon street of sense-city. As the days are different, we compare the temperature difference in the street canyon equipped with these cooling solutions with that on the surrounding area. This method allows us to overcome daily variations. To interpret the results, we analyse the shades and we follow the temperature over time and not only during the hottest hours. We also calculate the UTCI (Universal Thermal Climate Index) to compare the perceived temperature.

Findings: The results show that despite its small size, the canyon street of sense-city behaves like a canyon street and that the measured temperature differences due to heat exchanges comply with physical laws and that the number and spatial distribution of sensors is validated. The Sense-city demonstrator can therefore be used to carry out thermal efficiency experiments. In addition, the method we used to compare cooling solutions allows us to limit the impacts due to slight daily variations. Finally, while watering is effective in rapidly lowering the temperature in the street, shading remains an optimal solution for the perceived temperature, even if it would be ideal to close them at the end of the day to allow air circulation.

1. Introduction

During the months of July and August 2021, 2022 and 2023, numerous climatic disturbances such as heat domes in Canada, floods and landslides in Belgium, Germany, Turkey, China and giant fires in Russia, Canada and Greece marked news and people's minds. Climate inertia and the complexity of changing the energy model at the global level make it necessary to adapt our regions and cities to

* Correspondant author.

E-mail addresses: anne.ruas@univ-eiffel.fr (A. Ruas), bruno.barroca@upem.fr (B. Barroca), yan.ulanowski@univ-eiffel.fr (Y. Ulanowski).

<https://doi.org/10.1016/j.uclim.2024.101874>

Received 23 August 2023; Received in revised form 27 February 2024; Accepted 17 March 2024

Available online 27 March 2024

2212-0955/© 2024 The Authors. Published by Elsevier B.V. This is an open access article under the CC BY-NC license (<http://creativecommons.org/licenses/by-nc/4.0/>).

limit the impacts of the changes that are underway. The adaptation of territories, associated with imperative efforts on mitigation, is therefore an essential strategy to maintain the quality of life of living organisms (humans, fauna and flora) and limit the costs linked to the disorders caused by these events. This involves improving warning and crisis management systems (fires, heat waves, floods, hurricanes, health crises), but also urban, peri-urban and rural developments to mitigate the effects of these recurring crises and to adapt the territories to the climates of the future. Well aware of these issues, governments and regions can define laws or regulations, they can also rely on labels and standards put in place by international organizations such as ISO or national in order to manage the transition. This management can take multiple forms such as the ISO 37101 standard, or more specific application standards with actions relating to a particular issue. Adaptation strategies concern all countries. (Agboola et al., 2023) propose approaches for minimizing the effects of climate change in Nigerian cities.

This article focuses on the issue of urban cooling from French cases, even if the conclusions also apply in other contexts. In France, in accordance with the Grenelle environmental laws and then the NOTRe law, the Regional Scheme for Planning, Sustainable Development and Territorial Equality (SRADDET), drawn up by the regional council, sets medium- and long-term objectives in connection with several themes including the fight against climate change. The Territorial Climate Air Energy Plans (PCAET), SCoT and PLUi are then drawn up by the EPCIs (group of local authorities) to make the plans operational at the local level. The regulations evolve over time and in the end the action is carried out at the local level, by local authorities and by a set of actors, including private actors through the realization of development projects (public-private alliance for Implementation).

The urban heat island phenomenon is well known and very well documented in the scientific literature (Oke, 1987). Much research has been undertaken to compare cooling solutions (Santamouris, 2014; Santamouris et al., 2017; Bernard et al., 2020) resulting in guides presenting the solutions in a qualitative and educational way. Based on a rich scientific literature, the guide produced for ADEME (The French Agency for Ecological Transition) (Leroy et al., 2021) classifies cooling solutions into green, grey and soft solutions, and summarizes the research results characterizing cooling, the co-benefits and the impacts negatives of the main current solutions.

Many current research studies attempt to estimate the reduction in temperature induced by planning solutions (Kaloustian et al., 2018), reductions that are often limited given the small cooling spatial extent considered in the models or in the field. As limited as it might seem, local temperature reductions are important for urban planning on the one hand to build cooling islands and on the other hand to avoid thermal runaways.

The research work presented in this paper aims to compare the effectiveness of technical devices for urban cooling in the Sense-City urban demonstrator. This research is funded by the Fraicheur research program of the i-site FUTURE of the Gustave Eiffel University. The aim is to study the effectiveness of simple cooling solutions and to question the method and metrology associated with the experiments. The approach followed is empirical: it involves measuring air temperatures in the field. The research is conducted according to a comparative approach of devices during summer. These devices are placed in comparable urban and climatic conditions, which makes it possible to quantify and qualify the cooling performance comparatively. We therefore have two scientific objectives: to quantify the temperature differences according to the cooling devices and to set up and validate the experimental protocol in the Sense-City space.

1.1. Our research questions and choices

Sense-city is a new urban scientific demonstrator funded by the French Research Funding Agency (ANR). The objective of this equipment, described below, is to accelerate research on the urban transition, including that on the mitigation and adaptation of cities to climate change. Among the research subjects, one is linked to the adaptation of cities to heat waves. Sense-city being relatively small (each of the two experimental areas is limited to 400 m²), one of our first challenges is to study the suitability of the experimental area to explore the effectiveness of various cooling solutions. In particular a pseudo canyon street was built to study heat exchanges during heatwave periods. The canyon street is a classical urban shape widely used to study urban climate (Oke, 1987). Canyon street are still much studied (Muniz-Gaal et al., 2019) and used in urban climate simulation modelling as ENVI-met 4.0 (Muniz-Gaal et al., 2019) or TEB (Masson, 2000). Even if Sense-city canyon street is not all canyon street, does it behave as a real canyon street? What can we learn from this canyon street? What is its behaviour in periods of high heat? What is the heat dynamic in this street throughout the day? Can we refresh it using cooling solutions? Another question was about the sensors used in sense-city: are the sensitivity and deployment of sensors appropriate for comparing the temperature inside and outside the canyon street and for comparing cooling solutions to each other? At least, one challenge was to set up a method for comparing different close but not identical days.

Different solutions exist to cool cities. Some are simple and traditional (shading, light walls, presence of water) others are more recent, more expensive and more sophisticated such as the greening of roofs, cooling paving stones, the use of heat resistant materials for building or the design of the cooling system at the district level. Revegetation or renaturation is often popular because it is a no-regret solution that offers multiple benefits (EC, 2016; Anderson et al., 2022; Agboola et al., 2023). However, field studies show that the revegetation effort often does not compensate for the loss of plants due to the construction of roads and buildings (Barroca and Ruas, 2023). Many studies also prove that solutions are more efficient when they are combined (Santamouris et al., 2017) including hybrid green and grey solutions (Anderson et al., 2022). Sense-city canyon street has already 6 trees, including 3 water-trees. Our objective is thus to test other solutions that would complete the existing trees. Thus, for our experiments we chose very simple cooling solutions (shading, albedo change and watering) for different reasons. Firstly, these solutions are already used in cities such as Paris, so we know they can be deployed. Secondly these solutions have already been studied so we have knowledge describing their properties (Santamouris et al., 2017; Hendel et al., 2016; Parison et al., 2020), last but not least they are easy to install: they can therefore be tested one after the other in the same place, the same summer which minimises the difficulty of interpreting data due to a changing

context. Their study is relevant.

2. Experimental site and choice of sensors

2.1. Sense-city Tiny-District 2

Sense-city is an urban demonstrator, located in the scientific campus Cité Descartes in Marne-la-Vallée about ten kilometres East of Paris. Sense-city is made up of two experimentation areas, called Tiny-District 1 and Tiny-District 2, of 400m² each equipped with sensors. A climatic chamber of 450m² can be positioned on one of the two areas. Indeed, the climatic chamber is on rail and can be moved according to the needs on one or the other of the Tiny-District. Sense-city sensors are connected to an information system allowing access to data measured on time or in deferred time. The two experimentation areas house urban equipment allowing experiments to be carried out by researchers from different disciplines (Ruas, 2019). Fig. 1 represents the Tiny-District 2 in which we carried out experiments in July–August 2021 and July–August 2022. Tiny-District 2 consists of a street with sidewalks, two hollow walls 6 m high and 11 m long. Hollow walls allow heat to accumulate like buildings. These walls recreate a canyon street with heat exchanges. Tiny-District 2 also consists of 6 trees, including 3 rain trees. Rain trees have reservoirs to store rainwater flowing from the road. There is also a water garden and a mud house used for other experiments (Fig. 1). The researchers make an experiment record to be allowed to use Sense-City for a set period of time. As Sense-city is very recent - Sense city Tiny District 2 started to be used for scientific experiments in 2021 - experiments are often done several times to improve testing protocols.

2.2. Choice of sensors and sensor locations

The chosen sensors make it possible to compare one day with another and to measure the air temperatures in different places in space, at different heights, at different times. As part of this work, we focus on an experimental and non-modelling approach, so we mainly use air temperature sensors positioned at different locations. Thus, we modify the initial environment by including standard cooling devices that we leave at least 24 h to study the thermal variations over the hours.

To compare the days, we used a classic Meteorology sensor (Vaisala WXT536) and a radiation sensor (CampBell-NR-LITE2-L). We also used hygrometry measurements (CampBell HygroVUE 5). For the air temperature we used PT100 sensors integrated in shelters. All sensors are connected to data acquisition units (PEGASE, ADAM or CampBell).

The air temperature sensors were placed in 2021 at 50 cm from the ground and at 3 m to properly measure the heat dissipation effect. Once these effects were clearly demonstrated in 2021, we placed the sensors high at 2 m, which is the standard height for measurements. For the 2022 campaign, UTCI sensors have been added at 2 m.

Table 1 and Fig. 2 summarize the number and position of sensors for the two measurement campaigns. In terms of positioning, the reference sensors are positioned in the canyon street (point A in Fig. 2) and outside the canyon street (point B in Fig. 2). In 2021 we positioned the sensors on point A and B on the sidewalk, in 2022 we positioned them in the middle of the road to have a more central temperature in the canyon street. The other temperature sensors distributed in space allow us to calculate temperature fields and to have an average temperature outside the canyon street (without taking the sensors at point A).



Fig. 1. Tiny-District 2 from the sky (left) and from the north view point (right).

Table 1
Quantity and type of sensors for 2021 and 2022 measurement campaigns.

Type and height	Météo 7 m	Net Radiation 3 m	Hygrometry 3 m	Air temp. 0.5 m	Air temp. 3 m	Air Temp. 2 m	UTCI 2 m
2021	1	1	3	6	6	0	0
2022	1	1	3	5	0	9	3

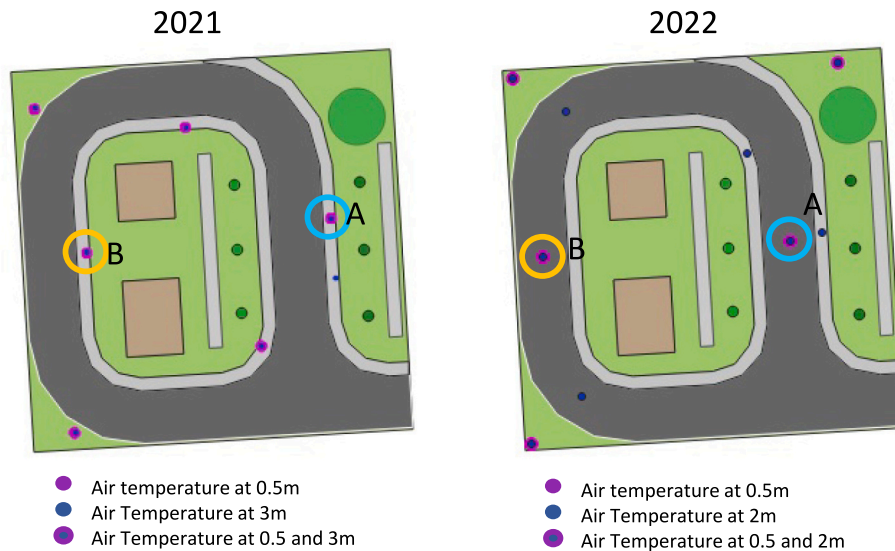


Fig. 2. The location of Air temperature sensors in 2021 and 2022.

2.3. Sensors calibration and accuracy

Sense-city temperature sensors are regularly calibrated at the COSYS laboratory which has equipment and personnel allowing these regular calibrations. Other sense-city sensors are calibrated by private companies. The information system in place makes it possible to know the calibration dates to be sure to only use calibrated sensors. The PT100 temperature sensors have an uncertainty of around $0.1\text{ }^{\circ}\text{C}$. If we take the example of sensor A (Fig. 2) its uncertainty is $0.08\text{ }^{\circ}\text{C}$ during its calibration, which is extended to $0.15\text{ }^{\circ}\text{C}$ for outdoor experiments. To study how this sensor behaved, we compared the sensor values in relation to the temperature trend during a night in an anticyclonic period. We chose the night of July 21, 2021 which was a warm night with very little wind and where the sense-city sensors had very homogeneous values. Between 1 a.m. and 5:30 a.m., the temperature cooled down regularly. We thus calculated the regression line then the deviation of the values from the sensor to this regression line which is a way of estimating the accuracy of this sensor. The quadratic sum of the deviations from the regression line is $\pm 0.10\text{ }^{\circ}\text{C}$. Thus, in real conditions, it is estimated that the sensor has an accuracy of $0.10\text{ }^{\circ}\text{C}$ which is consistent with the values of its calibration certificate. We can therefore consider that we will not be able to interpret results whose values are less than $0.1\text{ }^{\circ}\text{C}$.

3. Experiments and analysis methods

3.1. Choice of cooling solutions tested

The aim of our experiments is to estimate and compare air temperature differences according to site effects (canyon street) and cooling devices:

- Inside and outside canyon street to see the effect of this street on temperatures over the course of a day.
- With and without a cooling device in the canyon street (at point A) to study the effect of each cooling device.

Measurements are made at different heights to study the effect of heat dissipation. In terms of the choice of cooling devices, after an initial analysis (Clémence, 2021), we chose to test so-called grey devices, according to the ADEME nomenclature (Leroy et al., 2021). Among the possible grey devices, we have chosen three whose interest lies in the simplicity of technical implementation (for a local authority). We chose to test shading (two types of shading were tested), colour (by increasing the albedo of the ground) and watering (of the street). These solutions are classic and well documented. Shading and watering have a local effect, and are adapted to the human well-being (Leroy et al., 2021). Changing albedo can have a more global effect on the city if applied over a large area. It is not very suitable for pedestrians since it reflects the sun's rays during the hottest hours (Leroy et al., 2021). Yet many pedestrian squares in France, such as the Place de la Comédie in Montpellier, have light-colour floor covering. Street watering is studied, among other things, because it is a solution considered by various local authorities and already tested locally by the city of Paris in a sector that does not have the sensor density of Sense-city. Paris has a drinking water network and a substantial non-drinking water network that can be used to carry out actions to reduce urban temperature (Hendel et al., 2016; Parison et al., 2020). For shading, we are studying two types of shading: an opaque shading and an openwork shading (by 50%) to see if the difference is perceptible at the scale of the tiny-district 2.

So, by taking these three solutions, we compare, in the same space, the effectiveness of:

- Shading, opaque and openwork, which reduces solar radiation.
- The albedo which limits the accumulation of heat in the ground by reflecting more direct radiation.
- Evaporation which consumes part of the energy from solar radiation.

Assuming that the canyon street is a little warmer than the surrounding space, we study the effectiveness of these solutions to lower the temperature in the street at the central point A compared to point B (Fig. 2) depending on the solutions deployed.

3.2. Experiments in July 2021

The first year was used to test and calibrate the cooling devices and metrology for carrying out experiments during the 2022 campaign. In particular, it was important to validate or improve the number, type and position of sensors for the experiments. The summer of 2021 having been generally cool and rainy, only a series of five hottest days could be kept (Table 2), but the last day could not be used due to weather degradation.

3.3. Experiments in July–August 2022

As the summer of 2022 was particularly hot, many experiments were carried out (Table 3). Given the analyses of the 2021 data, we have chosen to use larger cooling surfaces and two types of shading:

- 24 m² white shade installed from 6 am to 6 am the next day.
- 24 m² openwork shading installed from 6 am to 6 am the next day.
- 35m² of white canvas on the ground from 6 am to 6 am the next day.
- A watering of 6 times 20 l on 24 m² of the road, sprayed 6 times from 1 pm to 3:30 pm (every 30 min).

In total we carried out 17 days of experiments. The experiments are sometimes carried out several times to obtain the most comparable days possible in terms of climate. Among these 17 days we keep 4 days representing different cooling devices and 2 reference days with no cooling devices: a standard day and an extreme heat wave day.

3.4. Comparison of cooling solutions

Even during a heat wave, every day is different. In 2021, in particular, we were not in a heatwave period, we used the net radiation to compare the days and eliminate the last day which was too cold. In July and August 2022, there were many hot and sometimes scorching days. These are the days of 2022 that we will use to compare cooling devices. However, despite a very hot summer, when we

Table 2

Experiments in July 2021.

20/07/2021	21/07/2021	22/07/2021	23/07/2021	24/07/2021
Reference day	Shady (Fig. 3, left)	White colour (Fig. 3, middle)	street watering (Fig. 3, right)	Watered trees
	Less Radiation	Higher Albedo	More evaporation	More evapo- transpiration



Fig. 3. Cooling devices used in July 2021.

Table 3

Experimentation days in July-august 2022.

	Reference days	Shading	Open shading	White street	Street watering
Number of days tested	6	5	4	1	1
Number of days retained	2	1	1	1	1



Fig. 4. Cooling devices used in July-august 2022.

look in detail, there are variations from day to day, from hour to hour, which can be explained by the general weather conditions, slight variations in the wind or a few passages of clouds.

Our objective being to study the effect of the cooling devices set up in the canyon street compared to the same place without cooling device, we chose to study the difference between the temperature in the street canyon (point A, Fig. 2) to the average of the other temperatures of Tiny-District 2, which allows us to overcome the meteorological differences between days.

4. 2021 campaign results: effect of sunshine and canyon street

4.1. Chronicle of a typical day

In the graph below (Fig. 5) in Tiny-District 2, the coolest time is 6:15 am (16.83 °C) (Paris time, so 4:15 h in Universal Time UT) and the hottest is 4:00 pm (29.86 °C) (i.e. 2 pm in UT). Fig. 6 shows that the temperature accumulates in the canyon street between 4 pm and 6 pm compared to the other sensors and then the temperature becomes homogeneous during the night. The maps in Fig. 6 are computed with the Inverse Distance Weighted interpolation function.

4.2. The effects of sunlight and dissipation

By observing the air temperatures at 50 cm and at 3 m over time at the same place (point B in Fig. 7) we see that:

- From 5 pm to 8:30 am the temperatures at 50 cm are warmer than at 3 m by an average of 0.4 °C. This corresponds to the phenomenon of conduction, convection and dissipation. The ground has stored heat during the day and radiates it at night. The air is warmer next to the ground (at 50 cm) than at 3 m.
- Between 9 am and 5 pm the values change:
 - Between 9 am and 12 pm, the upper sensor at 3 m is 1 to 2 °C warmer than that at the bottom.
 - Between 12 pm and 4:30 pm, it is the lower one (50 cm) which is warmer by about 1 °C.
 - Between 4.30 pm and 5 pm the upper sensor (3 m) is warmer.

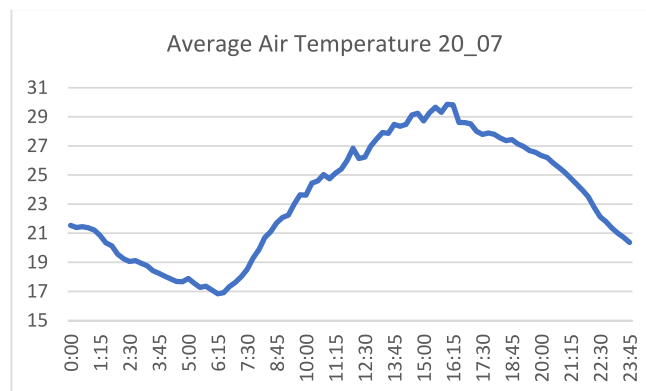


Fig. 5. Average temperature in Tiny-District 2 of the reference day of 2021.

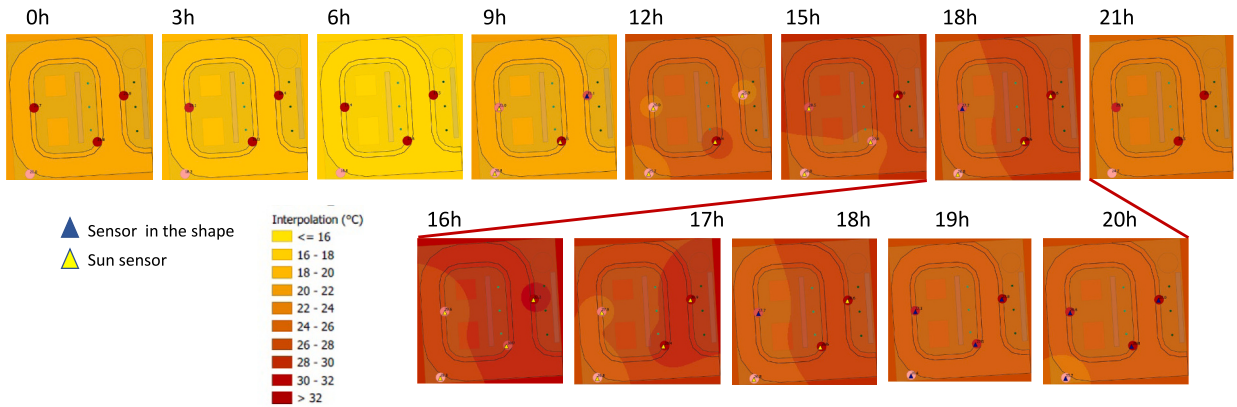


Fig. 6. Temperature field in Tiny-District 2 during a summer day.

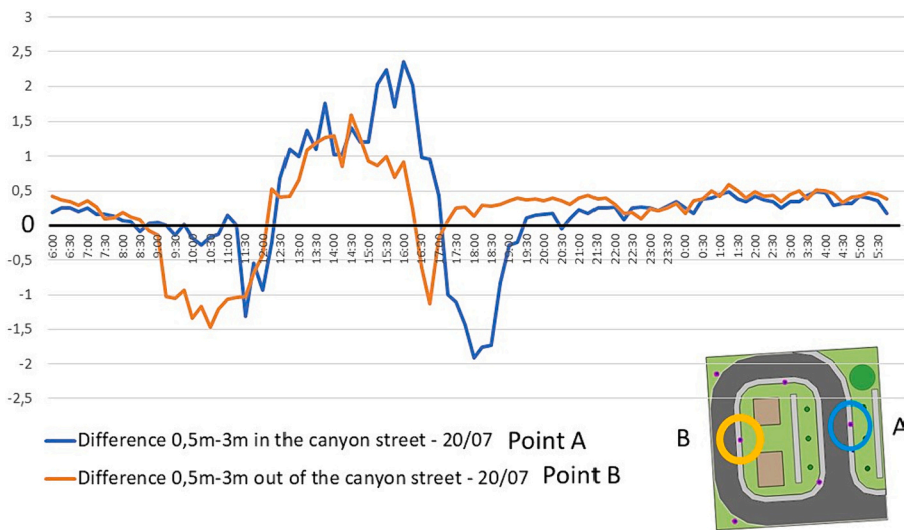


Fig. 7. Sun and dissipation effects.

- At 5 pm we return to the nominal situation where the temperature at 50 cm is warmer than that at 3 m.

The examination of the situation using 3D modelling and ephemeris data shows that the upper sensor is warmer than the lower sensor only when it is the only one of the two to be sunny (so between 9 am and 12 pm, and between 4.30 pm and 5 pm).

The shadow effect plays on points A and B but not at the same time (Fig. 8). For point A, which is located inside the canyon street (Fig. 7), the curve follows the same trends but given the configuration, the sensors are not sunny at the same time, which explains the time lag. On the other hand, we see that the effect is amplified: the temperature difference between the temperature at 50 cm and at 3 m is greater in the canyon street (point A) than outside the canyon street (Point B).

Fig. 8 shows the shadings on July 20, 2021 in Tiny-District 2 as a function of time. At 2 pm both sensors at point A in the middle of the canyon street are in the sun, while at 6 pm the top sensor is in the sun but the bottom one is in the shade. Fig. 9 shows the effect of sun exposure from sensors in Canyon Street on temperatures. From 6:00 am to 11:15 am the temperatures are almost identical. At 11:15 am (P1) the top sensor becomes warmer because it has moved into the sun while the one at 50 cm is still in the shade. As soon as the sensor at 50 cm goes into the sun (P2 Fig. 9) it becomes warmer than the other until it goes back into the shade (P3 Fig. 9) while the sensor at 3 m remains in the sun until at around 6:15 pm (P4 Fig. 9). The sensor at 50 cm becomes slightly warmer again than that at 3 m with a moderate difference of less than 0.5 °C which decreases during the night (Fig. 7, blue curve). The curves “Sun_on_sensor” in Fig. 9 represent the time when the sensors were illuminated by the sun.

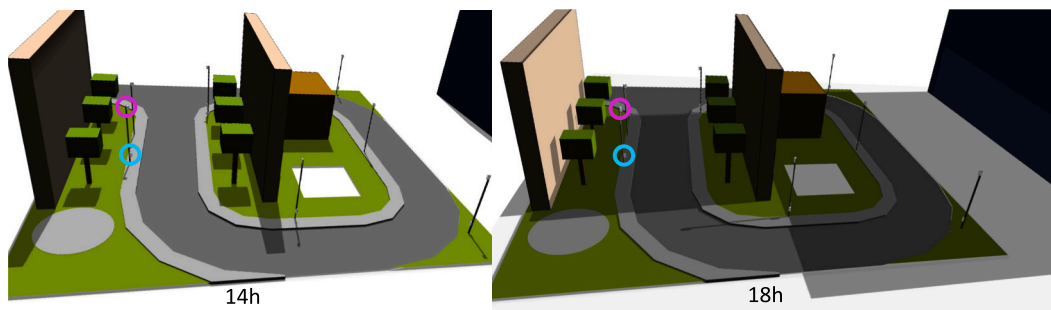


Fig. 8. Sun shadows on sensors located on point A (at 50 cm and 3 m), 3D view from the north side.

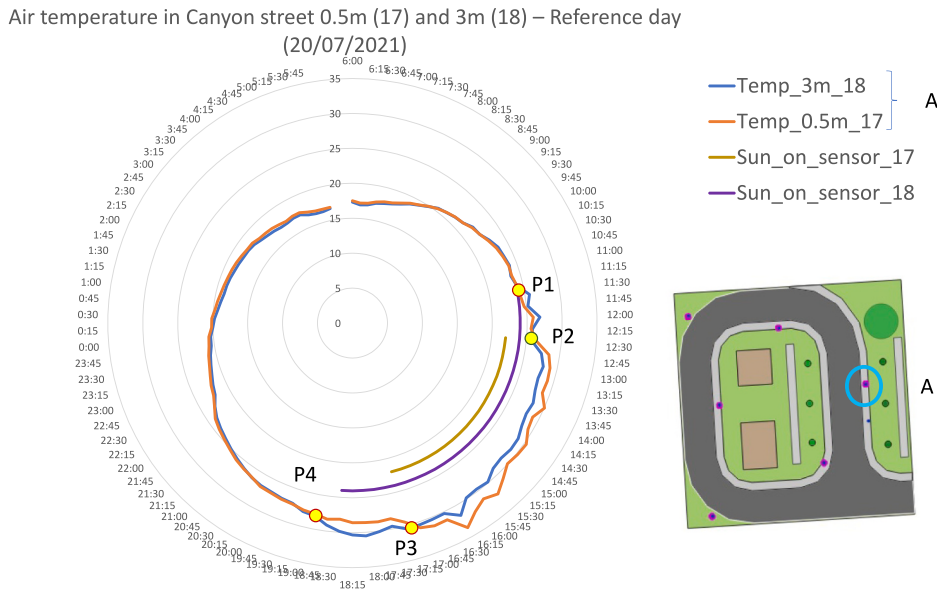


Fig. 9. Sun and dissipation effect inside the canyon street at 0.5 m and 3 m.

4.3. The street canyon effect

To evaluate the effect of the canyon street, we compare the temperature in the canyon street on the sidewalk (point A in Fig. 10) with a sensor in the same configuration but outside the canyon street (point B in Fig. 10). Fig. 10 illustrates the temperature at 3 m, the curves are even more marked at 50 cm. Both sensors have an equivalent positioning with respect to the winds. Here again, the temperature analysis must consider the sunshine of the sensors. In Fig. 10, between 9 am (P1) and 11:30 am (P2) sensor B outside the canyon street is 0.7 °C warmer than sensor A because it is the only one in the sun. As soon as the two sensors are in the sun, it is sensor A, include in the canyon street which is warmer by 1 °C. When the sensor B, outside the canyon street, goes into the shade (P3), the difference increases to 3 °C. Canyon Street still remains noticeably warmer by 1–2 °C until 7:30 pm (P4), then stays warmer all night by about 0.4 °C.

5. 2022 campaign results: comparison of cooling devices

5.1. Reference days

The reference days correspond to the sequence of consecutive hot days without cooling devices. We have selected 4 days between July 14 and July 19 which cover the temperature differences of the other days of experiments. These curves are quite similar, with the exception of the night of July 17 to 18 between midnight and 1 am when the temperature rose by more than 2 °C, which corresponds to a virtual absence of wind during that hour (Fig. 11).

Temperature at 3m, inside (18) and outside (22) the canyon street

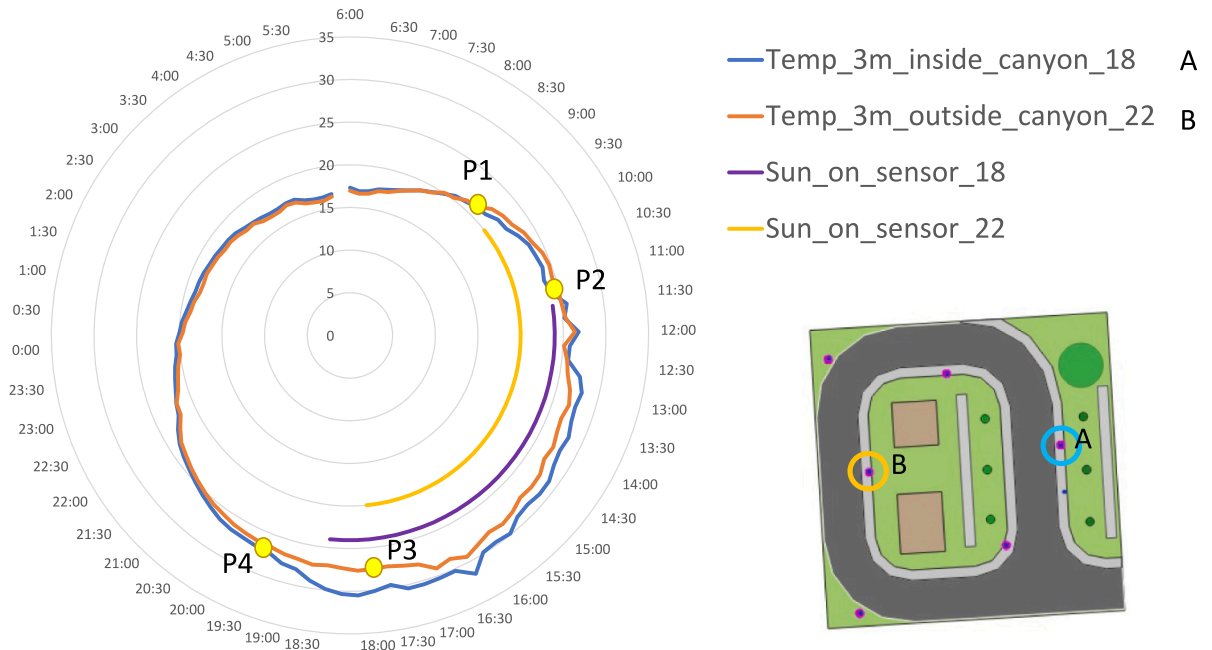


Fig. 10. Canyon and sun effect on air temperature inside and outside the canyon street at 3 m.

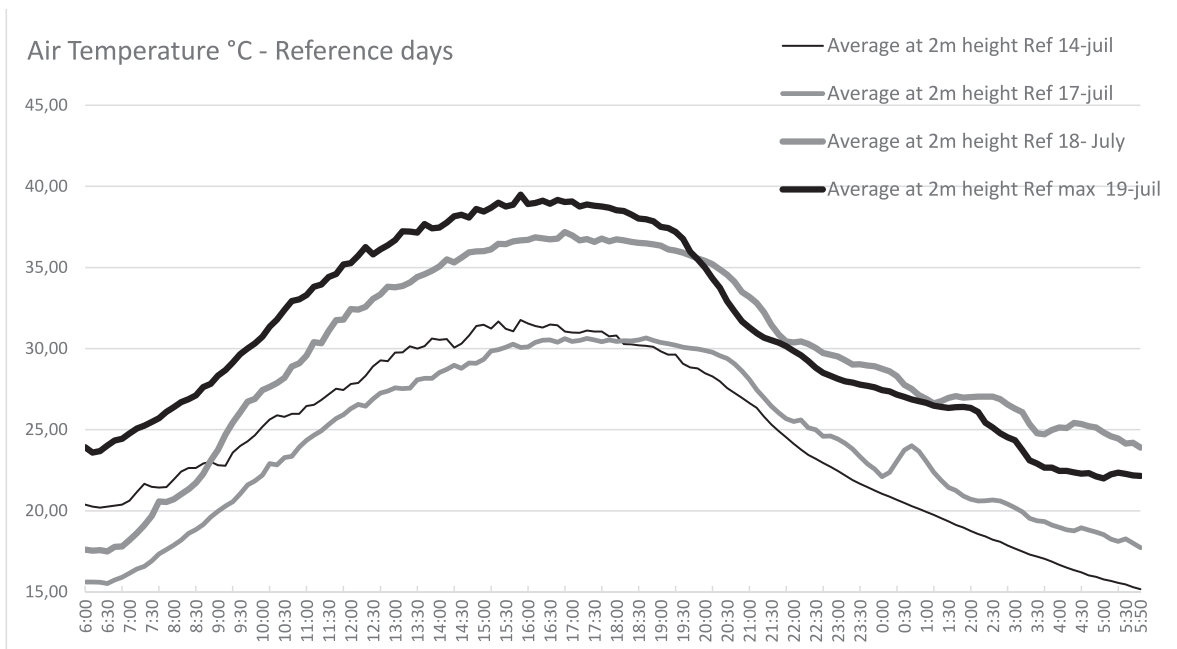


Fig. 11. The reference days: average temperatures at 2 m.

As the cooling devices are located in the canyon street, for the reference days we calculate the difference between the temperature in the canyon street (point A in Fig. 2) and the average of the other temperatures, which we compare with the days on which a cooling device is installed (see Fig. 4). In order to have a reference curve, we calculate the average curve of the differences for the 4 reference days, which makes it possible to smooth out the occasional differences due to wind variations (Fig. 12).

The average curve (green in Fig. 12) breaks down into three parts. The first part (Period 1) between 6 am and 10:30 am, the sun rises, some sensors are in the sun but not the sensor in the street canyon. It is therefore cooler in the canyon street from 7 am to 10:30 am. Then the canyon street starts to be in the sun and the temperature goes up. In period 2, the canyon street sensor is in the sun, the canyon street is clearly warmer than the average of the other sensors. In period 3 the sensors gradually move into the shade. The canyon street is slightly warmer than the other places, the difference decreases during the night. Note the particular shape of the morning of July 18 (Figs. 11 and 12), where the increase in temperature is greater than on other days and where there is no wind between 7 am and 9 am. That day the difference between the canyon street (in the shade) and the other measurement points was the greatest of the 4 days, which shows that the temperatures are more heterogeneous in the absence of wind.

For the rest of our research below, we use the average curve as a reference.

5.2. The cooling devices comparison

Fig. 13 below summarizes the results of the experiments. We first describe the curves by type of cooling device before concluding. In Fig. 13, each cooling device should be compared with the reference with no cooling device (green curve).

- Open or non-open shades have the following tendency:
- From 11 am to 3 pm the air temperatures are similar to the reference without shade.
- At the hottest hours between 4 pm and 5 pm, the shade devices save up to 0.5 °C (it is less hot), with an average of 0.3 °C between 3:45 pm and 5:45 pm compared to a situation in the street canyon without device. This trend is felt until 8 pm.
- At the end of the day from 9 pm to 1 am, it is the opposite, the shade seems to prevent the air from circulating, and the canyon street then becomes warmer by 1 °C than in a configuration without shade.
- At night the temperature becomes homogeneous again.
- On average over one day, the street is 0.1 °C warmer than the street without the device.
- Open or non-open shades are quite similar.

Changing the albedo of the road (white street) has the following effect:

- During the hottest hours, from 11 am to 5 pm, the white ground sends the radiation back into the street instead of absorbing it, it increases the air temperature by an average of 0.5 °C with peaks of 1 °C towards 2:30 pm compared to the reference and therefore reinforces the overheating effect produced by the canyon street. This is due to radiation that is reflected back into the street.
- On the other hand, from 9 pm, it is the most effective solution since there was less absorption of radiation and therefore less conduction. The floor material at the end of the day has accumulated less heat and therefore warms the space less than the other devices.
- On average over one day the street is warmer by 0.04 °C compared to the street without any device.

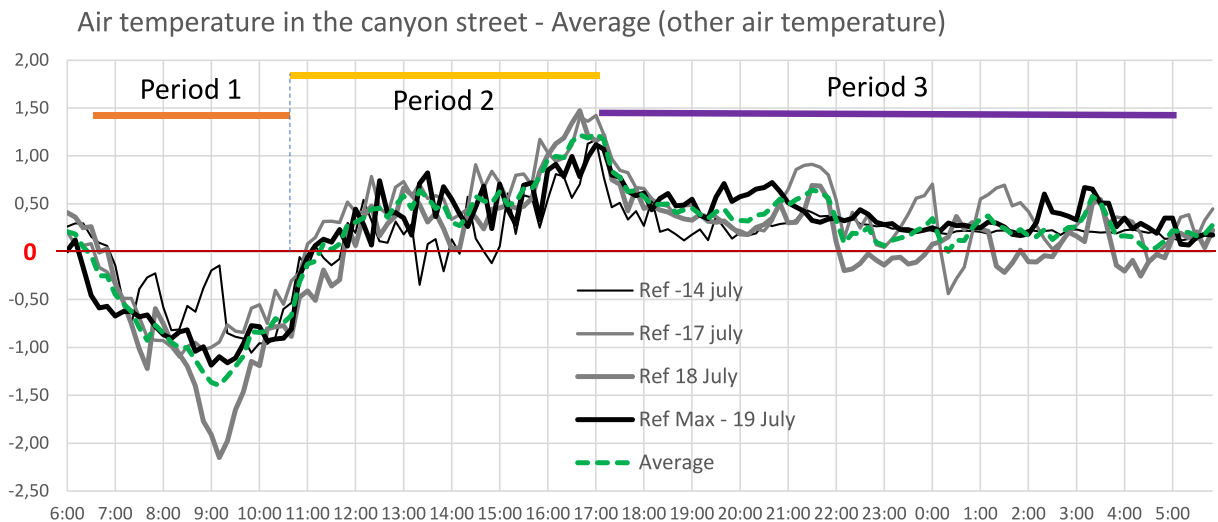


Fig. 12. Difference between the canyon street and the average temperature in the Tiny-District 2.

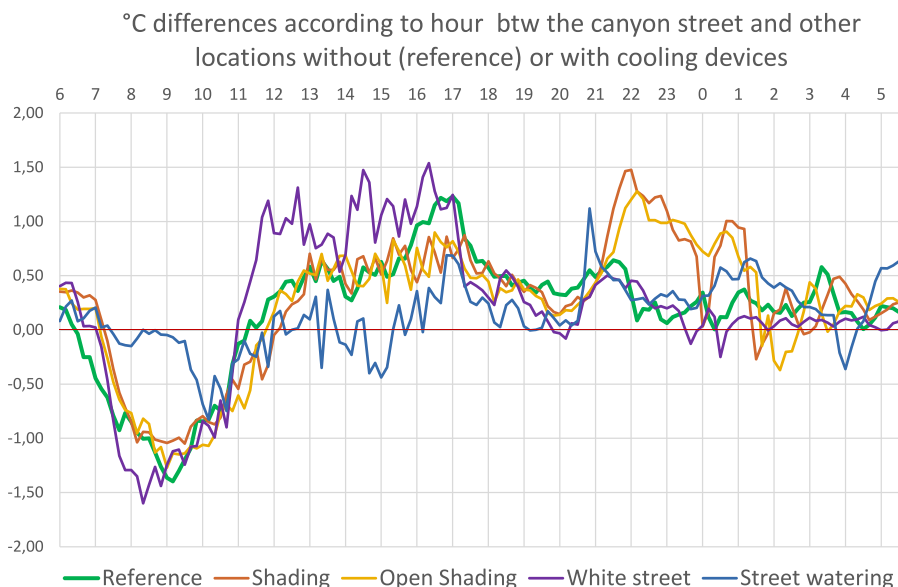


Fig. 13. Difference between the canyon street and the average outside temperature according to cooling devices in the canyon street.

- Street watering is carried out 6 times from 1 pm to 3:30 pm:
- Between 1 pm and 3:30 pm, watering is very effective in preventing the canyon street from heating up. It is the only device allowing there to be no difference between the canyon street and the surroundings, and lowers the temperature by 0.5 °C on average between 12 pm and 5 pm compared to the canyon street without device.
- As soon as the watering stops, the temperature rises but less heat has been accumulated in the soil material. The street is therefore warmer than the surroundings, but slightly cooler than without this cooling device.
- From 8 pm the effect is no longer noticeable. The canyon street remains a little warmer than the surrounding space.
- On average over one day, the street is cooler by 0.02 °C compared to the street without the device.

5.3. Calculating the UTCI

The air temperature does not translate the feeling, the UTCI is an index created in 2009 by the international society of Biometeorology to estimate this feeling. Heat stress refers to the inability of the human body to maintain normal body temperature due to excessively high temperature and humidity conditions. This exposes people to heat-related illnesses that can lead to death. The UTCI combines air temperature, wind speed, humidity and radiant temperature. To compute the UTCI values we use an UTCI sensor box acquired in 2022 that gives air temperature, radiant temperature under a black globe, wind speed and humidity. Then we use an UTCI calculator accessible on line <http://www.utci.org/utci/utci.php>. Between 9 and 26 °C UTCI, there is no heat stress, between 26 and 46 °C and above, there are four levels of heat stress: moderate (26 to 32 °C), strong (32 to 36 °C), very strong (36 to 46 °C) and extreme (above 46 °C). Fig. 14 presents the UTCI computed in the canyon street for the four cooling devices and the reference day.

Fig. 14 is not easy to interpret since the average temperatures were not identical each day and the UTCI requires taking the temperature values and not the differences in the surroundings as we did for the previous analysis. Fig. 15 describes the surrounding temperatures on those days and clearly shows the temperature differences between the days. We can clearly see that only full or open shading reduces thermal stress in the canyon street, while watering and the change in albedo are ineffective, even harmful.

6. Discussions

The experiments carried out in the sense-city space make it possible to highlight important elements for urban design and for relevant developments to combat urban heat during heat waves. The analyses carried out show that direct sunshine on the street is the main warming factor and that, in particular, direct sunshine on a canyon street significantly increases the air temperature compared to a more open environment (Figs. 10 and 12).

According to our analyses the change in albedo (lighter) is the worst solution for canyon streets since it does not reduce the overall temperature over the day and increases the air temperatures in the street during the warmest hours. However, this solution is surely optimal for rooftops, since then the reflected radiation reduces the heating of buildings without increasing the temperature of the street. It would be a simple and effective solution, for example, for the roofs of buildings located in open spaces such as peripheral industrial areas that are not organized in a canyon. For these areas, we could certainly suggest to associate them with unsealing or light floors, with the exception of the pedestrian paths leading to the entrances of the buildings, paths which could be dark to avoid reflected radiation.

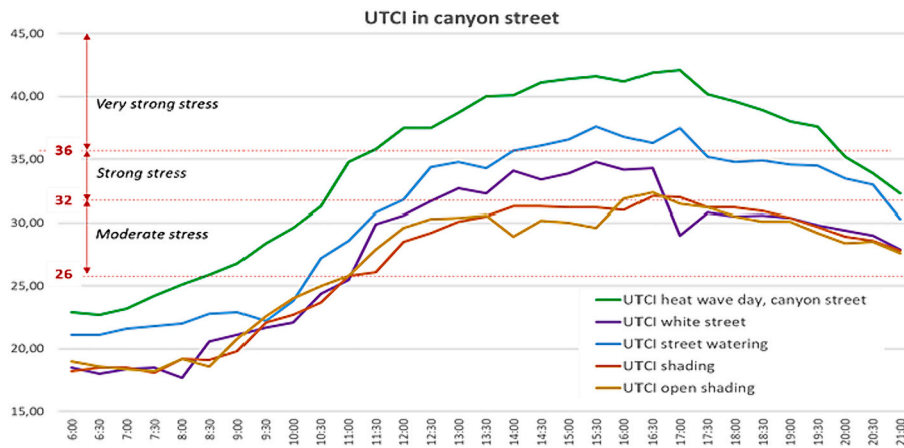


Fig. 14. UTCI according the cooling devices in the canyon street.

Watering is the most effective solution for cooling canyon street during the hottest hours (Fig. 13) and overall, but this system uses a resource that is often scarce. In addition, this solution is less effective in terms of feeling the heat (UTCI) than in terms of reducing the temperature (Figs. 13 and 15), as it does not protect people from direct sun radiation.

In absolute terms, the shade provided by buildings is the most effective. In fact, during the experiments, the canyon street in the shade from 7 am to 11 am was the least hot space. This is also the conclusion of the work of Lee et al. (2018) or Ali-Toudert et al. (2005) which emphasizes that the shading generated by buildings is very effective. Oke (1987, page 258) recalls the virtues of vernacular architecture in narrow, shaded streets in hot, dry countries to protect against the summer heat. To provide shade, we need therefore to distinguish the spaces to be built from the spaces already built. In the case of spaces to be built, the orientation of the streets, the height of the buildings, the materials are essential points to consider at the scale of the districts to reduce Urban Heat Island (UHI) (Boccalatte et al., 2020). When the space is already built, other shading solutions should be considered. Studies show that mature trees are good solutions (Kántor et al., 2018). In our case, we could not plant trees, we experimented with the use of classic shaded structures (in opaque fabric) or openwork (Fig. 4). The shades proved to be more effective for the heat felt than the other devices (Figs. 14 and 15), but we could not decide between open or not open shades. If in total over a day the shades do not cool the air temperature on average, they do, however, allow to slightly lower the air temperature during the hottest hours (from 4 pm to 5 pm) by 0.5 °C but above all to lower the UTCI by 1.5 °C on average between 11 am and 5 pm (Fig. 16), which is considerable. The prerequisite for mitigating heat stress in urban spaces is the reduction of mean radiant temperature which can be most effectively achieved by shading (Kántor et al., 2018; Ali-Toudert et al., 2005).

In our work, we did not test different forms of shading, but this type of analysis using software such as the ComfortCover method proposed by Vartholomaïos and Kalogirou (2020) would certainly be very relevant since the method allows the shape, orientation and geographical location of the shading to be considered in order to optimise its effectiveness.

The results we present are above all qualitative. They allow the efficiencies of the solutions to be ordered one to another and according to the hours but do not allow the temperature gains to be precisely quantified. The gains depend on the absolute temperature (Santamouris et al., 2017) but in addition on the context. The reduced size of sense city is also a factor of uncertainty. However, the order relationship between the solutions and the order of magnitude of the gains in degree remain interesting. Implementing these solutions in the real world raises further questions. If large cities like Paris are experimenting, other cities are slower and encounter

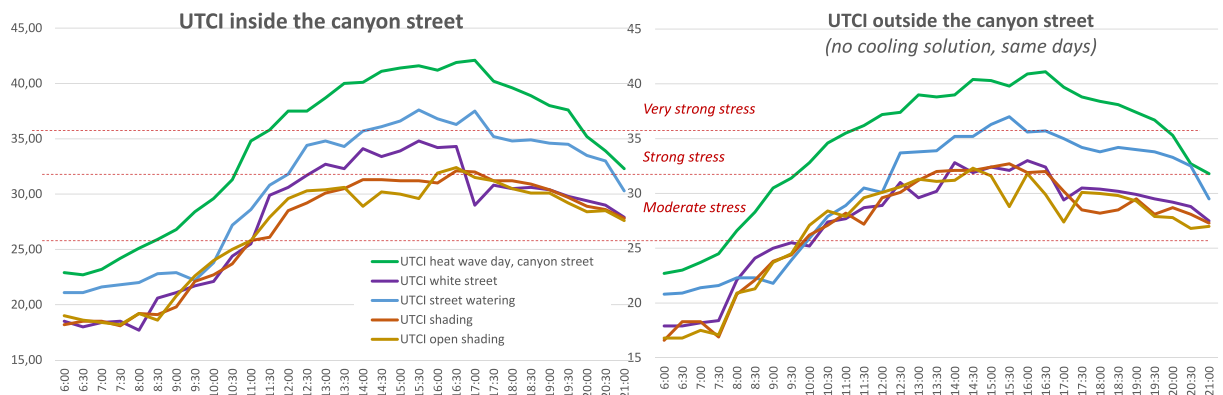


Fig. 15. UTCI according to the cooling devices in the street canyon (left) and outside the street canyon without cooling devices (right).

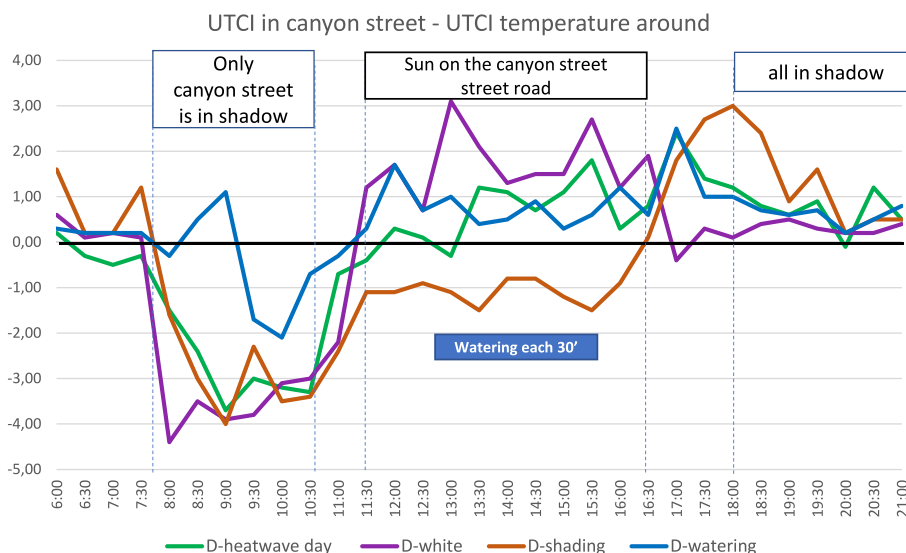


Fig. 16. Difference in UTCI values by device between UTCI in the canyon street and UTCI outside the canyon street.

various difficulties including citizen reluctance. The FreshWay research project, on which we are working, aims precisely to analyse the planification and concrete measures of urban cooling from several French communities.

7. Conclusion

This research highlights the measured effectiveness of cooling devices in an experimental situation. Elements measured concerning the effectiveness of the albedo (in “hot hours” and “cool hours”) and shading give original results. To sum up we could say that canyon streets, when they let in solar radiation, are particularly hot streets. They can be cooled by shading or street watering. Street watering is more effective than shading or albedo change in quickly reducing air temperature, but the effect does not last. Canyon street with light pavement (with high albedo) are not effective for pedestrians because they heat up the streets during the hottest hours. Shading pedestrian canyon streets is an effective solution for thermal comfort for sunny streets because it reduces radiation.

We also noticed that shading, which seems to be an interesting solution for the hottest hours, tends to slow down the cooling of streets at the end of the day, certainly through aerodynamic blockages (as shown in Fig. 13). More over canyon streets are spaces where pollution tends to accumulate, shade structures should not accentuate this tendency. Shading could be limited to pedestrian streets and the conception of the shading should be optimised to maximise shade and minimize aerodynamic blockage. For this, modelling is certainly the best approach because it would depend on many factors such as the shape of the canyon, its orientation and the direction of the dominant wind. Dynamic shading devices - open during the hottest hours and closed at the end of the day to allow optimal ventilation - might be a solution, but it has to be robust and unexpansive.

Our research also allowed us to study the use of the sense-city equipment to compare cooling devices. Thanks to this work, we have improved metrology for the comparative study of devices and proposed methods to minimize the impact of daily meteorological variations in our analyses. We were also able to observe that, although small in size, sense-city canyon street behaves like a classic canyon street in terms of heat exchange, which allows us to validate the relevance of the Sense City equipment for experimenting with this type of urban form. We can thus conclude that sense-city demonstrator, including its collection of sensors, is suitable for carrying out experiments on the performance of cooling solutions and that its canyon street, despite its small size, behaves like a real canyon street and can be used to carry out heat waves and cooling experiments.

Based on our results, it would seem relevant to consider future experiments, particularly with dynamic shading devices.

Funding

Fraicheur project, 2020–2022, funded by i-Site Future, University Gustave Eiffel, France.

CRedit authorship contribution statement

Anne Ruas: Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Conceptualization. **Valentin Clemence:** Software, Methodology, Investigation. **Bruno Barroca:** Validation, Conceptualization. **Yan Ulanowski:** Resources.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

References

- Agboola, O.P., Ojobo, H., Aliyev, A., 2023. Ameliorating climate change impacts on the built environment. *Civil Eng. Architect.* 11 (3), 1324–1336. <https://doi.org/10.13189/cea.2023.110317>.
- Ali-Toudert, F., Djenane, M., Bensalem, R., Mayer, H., 2005. Outdoor thermal comfort in the old desert city of Beni-Isguen, Algeria. *Clim. Res.* 28, 243–256.
- Anderson, C., Renaud, F., Hanscomb, S., Gonzalez-Ollauri, A., 2022. Green, hybrid, or grey disaster risk reduction measures: what shapes public preferences for nature-based solutions? *J. Environ. Manag.* 310 <https://doi.org/10.1016/j.jenvman.2022.114727>.
- Barroca, B., Ruas, A., 2023. Trajectoires de rafraîchissement urbain et planification urbaine. In: Briche, E. (Ed.), *Trajectoires de Transition écologique*. Eds Quae, pp. 249–267.
- Bernard, J., Musy, M., Marie, H., 2020. Rafraîchissement des villes : solutions existantes et pistes de recherche. In: *Adaptation au Changement Climatique et projet urbain*. Hal-02953445.
- Boccalatte, A., Fossa, M., Gaillard, L., Ménézo, C., 2020. Microclimate and urban morphology effects on building energy demand in different European cities. *Energ. Build.* 224 <https://doi.org/10.1016/j.enbuild.2020.110129>.
- Clémence, V., 2021. Étude comparative de l'effet rafraîchissant de différents composants urbains en période de canicule. Master thesis, Universités Côte d'Azur et Gustave Eiffel, p. 109p.
- EC, 2016. European Commission, 2016. Topics: Nature-Based Solutions. <https://ec.europa.eu/research/environment/index.cfm?pg=nbs>.
- Hendel, M., Gutierrez, P., Colombert, M., Diab, Y., Royon, L., 2016. Measuring the effects of urban Heat Island mitigation techniques in the field: application to the case of pavement-watering in Paris. *Urban Clim.* 16, 43–58. <https://doi.org/10.1016/j.uclim.2016.02.003>.
- Kaloustian, N., Aouad, D., Battista, G., Zinzi, M., 2018. Leftover spaces for the mitigation of urban overheating in municipal Beirut. *Climate* 6 (3), 68. <https://doi.org/10.3390/cli6030068>.
- Kántor, N., Chen, L., Gál, C.V., 2018. Human-Biometeorological Significance of Shading in Urban Public Spaces—Summertime Measurements in Pécs, Hungary, *Landscape and Urban Planning*, 241–255, p. 170. <https://doi.org/10.1016/j.landurbplan.2017.09.030>. ISSN 0169–2046.
- Lee, I., Voogt, J.A., Gillespie, T.J., 2018. Analysis and comparison of shading strategies to increase human thermal comfort in urban areas. *Atmosphere* 9 (3), 91. <https://doi.org/10.3390/atmos9030091>.
- Leroy, M., Marie, H., Lapray, K., Musy, M., Rodler, A., Guernouti, S., 2021. Rafraîchir des Villes, des Solutions Variées. ADEME, p. 80. ISBN: 979–10–297-1748-2.
- Masson, V., 2000. A physically-based scheme for the urban energy budget in atmospheric models. *Bound.-Layer Meteorol.* 94, 357–397.
- Muniz-Gaal, L., Pezzuto, C., Carvalho, M., Mota, L., 2019. Urban geometry and the microclimate of street canyons in tropical climate. *Build. Environ.* 169, 106547. <https://doi.org/10.1016/j.buildenv.2019.106547>.
- Oke, T.R., 1987. *Boundary layer climate*. In: Methuen London, 2nd Ed, p. 435 (ISBN 0-415-04319-0.).
- Parison, S., Hendel, M., Grados, A., Royon, L., 2020. Analysis of the heat budget of standard, cool and watered pavements under lab heat-wave conditions. *Energ. Build.* 228 <https://doi.org/10.1016/j.enbuild.2020.110455>.
- Ruas, A., 2019. Sense-city, un démonstrateur pour faciliter la transition urbaine. *Progettare l'Involucro Urbano 57–61* (Wolters Kluwer, ISBN: 9788859820703).
- Santamouris, M., 2014. Cooling the cities - a review of reflective and green roof mitigation technologies to fight heat island and improve comfort in urban environments. *Sol. Energy* 103, 682–703. <https://doi.org/10.1016/j.solener.2012.07.003>.
- Santamouris, M., Ding, L., Fiorito, F., Oldfield, P., Osmond, P., Paolini, R., Prasad, D., Synnefa, A., 2017. Passive and active cooling for the outdoor built environment—analysis and assessment of the cooling potential of mitigation technologies using performance data from 220 large scale projects. *Sol. Energy* 154, 14–33. <https://doi.org/10.1016/j.solener.2016.12.006>.
- Vartholomaios, A., Kalogirou, N., 2020. Optimisation of outdoor shading devices with thermal Comfort criteria: the case of the venetian port of Chania. In: *IOP Conf. Ser: Earth Environ., Sci.* <https://doi.org/10.1088/1755-1315/410/1/012058>.