# Improving Pedestrian Thermal Comfort by Pavement-Watering during Intense Heat Events

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**ABSTRACT**

*From the late 19th until the mid-20th Century, pavement-watering was used to prevent dust cloud from forming. This practise has since been lost, but is now stirring new interest as a tool for urban heat island mitigation, climate change adaptation and pedestrian thermal stress reduction. To evaluate the potential of pavement-watering, two daytime watering methods were tested over the summer of 2013 in Paris, France: the pavement and sidewalk of a N-S street and the pavement of an E-W street. The effectiveness of the method was measured according to mean radiant temperature (MRT) and Universal Thermal Climate Index (UTCI) equivalent temperature reductions, determined by a statistical analysis. MRT and UTCI reductions were observed at both sites. While daily effects were highest at the N-S site, highest maximum hourly cooling was observed at the E-W site, reaching 2.9°C for MRT and 1.2°C for UTCI. Overall, hourly cooling was most often statistically significant at night and at the N-S site.*

## INTRODUCTION

Paris' strong hygienist movement during the 19th Century led to the development of its dual water supply. Street cleaning has since relied on the use of non-potable water. Until the mid-20th Century, streets could be watered up to five times a day on hot summer days to prevent dust clouds from forming (Girard, 1923). According to reports by urban managers at the time, many inhabitants also it had a cooling effect. As mechanized cleaning was generalized, these practises were lost and nearly forgotten.

Urban areas, through a combination of radiation trapping, wind obstruction, and low surface humidity, create a localized warming effect know as the urban heat island effect (Grimmond, 2007; Oke, 1973). Today, climate change is expected to increase the frequency and intensity of heat-waves on all continents, including in the Paris region (Lemonsu, Kounkou-Arnaud, Desplat, Salagnac, & Masson, 2012). Unfortunately for urban dwellers, heat-waves have been found to interact with urban heat islands and increase their intensity (Li & Bou-Zeid, 2013). This mechanism helps explain why heat-waves are more devastating in densely populated cities than in rural areas, such as was the case in Paris during the August 2003 heat-wave (Robine et al., 2008). Adaptation to more frequent and more intense heat-waves is therefore crucial in dense cities.

In this context, pavement-watering may once more have a role to play in cities as an emergency counter-measure against heat-waves. By artificially reintroducing the evaporative mechanism at work in rural soils, pavement-watering is expected to positively impact pedestrian thermal comfort by reducing surface and air temperatures, while only marginally increasing air humidity.

In Japan, field and numerical studies of pavement-watering have been carried out over the last twenty years or so (Kinouchi & Kanda, 1997, 1998; Nakayama & Fujita, 2010; Nakayama & Hashimoto, 2011; Takahashi, Asakura, Koike, Himeno, & Fujita, 2010; Yamagata, Nasu, Yoshizawa, Miyamoto, & Minamiyama, 2008). In Paris, computer simulations of the method at the city-scale (Météo-France & CSTB, 2012) have been conducted in recent years as well as pavement-watering field experiments (Bouvier, Brunner, & Aimé, 2013).

Review of previous field work reveals strong variability in the micro-climatic effects of pavement-watering as well as in their measurement methodology. Reported air cooling ranges from 0.4°C to 4°C, while measurement heights vary from 0.5 m to 2 m (Bouvier et al., 2013; Takahashi et al., 2010; Yamagata et al., 2008). Furthermore, only a few studies study the effect on pedestrian thermal comfort. This variability in methods only highlights the need for standardization in urban micro-climatic measurements as was outlined by Johansson, Thorsson, Emmanuel, & Krüger (2014).

To better understand the potential of pavement-watering to improve pedestrian comfort in Paris, two watering methods were tested over the summer of 2013 at two locations: rue du Louvre in the 1st and 2nd Arrondissements and Belleville in the 20th Arrondissement. This article will present the method used to analyse field measurements and the effects of pavement-watering on pedestrian thermal comfort as estimated by mean radiant temperature (MRT) and the Universal Thermal Climate Index (UTCI).

## MATERIALS AND METHOD

Micro-climatic parameters were investigated at two sites in Paris, France over the summer of 2013, hereafter referred to as Louvre and Belleville. For the former, measurements were conducted on rue du Louvre, near Les Halles in the 1st and 2nd Arrondissements, while at Belleville they took place on rue Lesage and rue Ramponeau in the 20th Arrondissement. Watered and control weather station positions are illustrated in Figure 1. Two twin weather stations were positioned for each site, each pair measuring identical parameters. Each position was chosen to ensure that the urban environment of each station was as identical as possible (traffic, materials, urban morphology, sky view factor, …).

On rue du Louvre, watering took place on the sidewalk and pavement, each paved with asphalt concrete. Both watered and dry portions of the street are approximately 180 m long and 20 m wide. The street canyon has an aspect ratio approximately equal to one (H/W=1) and has a roughly N-S orientation.

At Belleville, watering was limited to the cobblestone pavement only. The watered portion was located on rue Lesage while the dry portion was on rue Ramponeau, a parallel street nearby. The watered portion was approximately 40 m long and 4 m wide. Both canyons have an aspect ratio approximately equal to one and have a roughly E-W orientation.

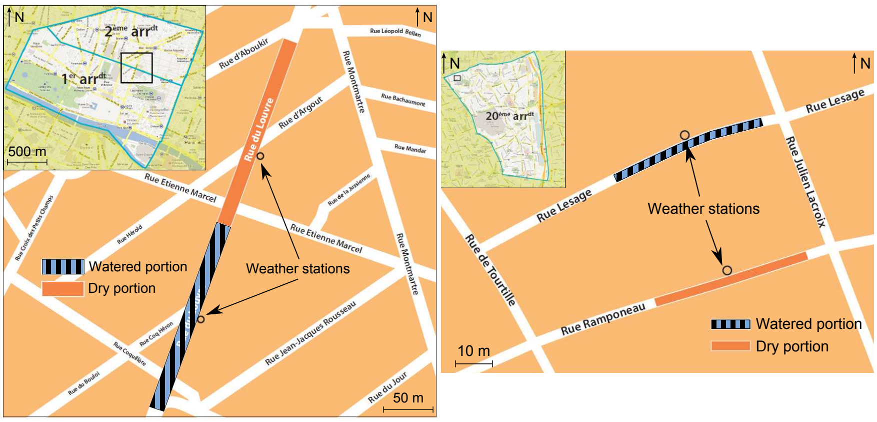


*Figure 1: Map of weather station positions at the Louvre (left) and Belleville (right) test sites.*

### Instruments

Weather station design is presented in Figure 2. Instruments within pedestrian reach were protected behind a 2-m cylindrical white-painted steel cage. All parameters were recorded every minute and smoothed with a one-hour moving average. The final series was obtained by keeping four data points per hour from the smoothed series. All data is presented in local daylight savings time (UTC +2). Table 1 lists the instruments used for this analysis as well as their height and accuracy.

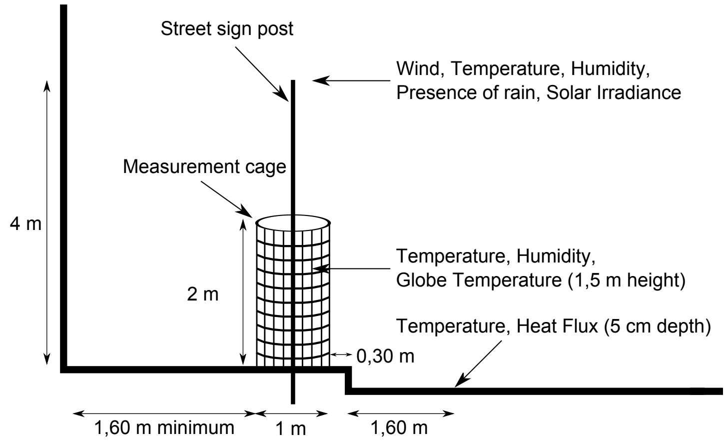


*Figure 2: Weather station design and instrumentation. The temperature and heat flux sensor was only installed at the Louvre site.*

**Table 1: Instrument type, measurement height and accuracy**

| Parameter | Instrument | Height | Accuracy |
|---|---|---|---|
| Air temperature | Sheltered Pt100 1/3 DIN B | 1.5 m | 0.1°C |
| Relative humidity | Sheltered capacitive hygrometer | 1.5 m | 1.5% RH |
| Black globe temperature | Pt100 1/2 DIN A - ISO 7726 | 1.5 m | 0.15°C |
| Wind speed | 2D ultrasonic anemometer | 4 m | 2% |

**Thermal comfort evaluation**

The effects of pavement-watering were quantified by MRT and UTCI.

Since we are studying the potential for pavement-watering to reduce the health impacts of intense heat-waves, one of the indexes should be able to properly assess heat-related health impacts. Thorsson et al. (2014) found that MRT was a better predictor for heat-related mortality than air temperature, which is more commonly used. MRT was therefore chosen for these reasons.

However, although it may be effective at predicting heat-related mortality, MRT is a relatively new index for heat stress and does not currently allow us to evaluate intermediate levels of heat stress. Furthermore, it ignores the effects of wind speed, air temperature or humidity on thermal comfort. We therefore need to include an index that takes all relevant climatic aspects into account.

One of the more recently developed thermal comfort indexes is the Universal Thermal Climate Index (UTCI) (Blazejczyk et al., 2010). UTCI was developed by international experts from Commission 6 of the International Society of Biometeorology (ISB) and European COST Action 730 from the year 2000 to 2009. It is based on a special version of the multi-node Fiala thermophysiological model. Air temperature, humidity, wind speed and MRT are used as well as assumptions on the metabolic activity and clothing of pedestrians to calculate an equivalent air temperature for reference conditions.

To calculate MRT, black globe temperature ($T_g$), air temperature ($T_a$) and wind speed (v) measurements from the weather station were used according to the method described by ASHRAE (2001). Air temperature, relative humidity, MRT and wind speed measurements were then used to obtain UTCI equivalent temperature, which was fast-calculated with the FORTRAN code written by Peter Bröde in 2009, adapted for use with the R software environment. The source code is freely available at http://www.utci.org/utci_doku.php.

Inaccuracies are introduced into both MRT and UTCI by the use of 4-m wind speed rather than 1.5-m and 10-m wind speed, respectively, as well by globe temperature measured inside the cylindrical cage.

**Watering method**

Watering was started if certain weather conditions were met based on Météo-France's three-day forecast. These as well as those for heat-wave warnings in Paris are presented in Table 2. $BMI_{Max}$ and $BMI_{Min}$ refer to the 3-day mean of maximum ($T_x$) and minimum ($T_n$) air temperature.

At the Louvre site, cleaning trucks were used to sprinkle sidewalk and pavement every hour in the morning (6:30 am to 11:30 am) and every 30 minutes in the afternoon (2 pm to 6:30 pm). At the Belleville site, a removable 40-m watering pipe was laid along the gutter to water the pavement on rue Lesage continuously from 7 am to 7 pm. In terms of the watered surface ratio, rue du Louvre was 100% watered, while rue Lesage was approximately 33% watered. Water used for this experiment was supplied by the city's 1,600-km non-potable water network, principally sourced from the Ourcq Canal.

**Table 2: Weather conditions required for pavement-watering and heat-wave warnings**

| Parameter | Pavement-watering | Heat-wave warning level |
|---|---|---|
| $BMI_{Min}$ | ≥ 16°C | ≥ 21°C |
| $BMI_{Max}$ | ≥ 25°C | ≥ 31°C |
| Wind speed | ≤ 10 km/h | - |
| Sky conditions | Sunny (less than 2 oktas cloud cover) | - |

**Data selection and interpretation method**

Because many weather conditions were encountered over the duration of the experiment, only days of Pasquill atmospheric stability class A-B or more were retained for the upcoming analyses (Pasquill, 1961). This provision limits selected days to those with clear skies (less than 3 oktas) and low wind speeds (less than 3 m/s).

To interpret the effect of pavement-watering on MRT or UTCI, the difference between the watered and control stations is analysed, calculated as: $y_{difference}=y_{watered} - y_{control}$. Negative values indicate that the watered station parameter is lower than that of the control station, and vice versa.

However, even with these provisions in mind, it is not possible to determine the effect of pavement-watering by analyzing the raw data from the weather stations. To eliminate the high natural variability in the data, a statistical representation of the daily profile of the difference is used instead, calculated for dry (control) days and case (watered) days.

Finally, because no watering occurs between midnight and 6 am, days will be divided into 24-hour periods beginning at 6 am and ending at 5:59 am the next day. Thus, when we refer to data from July 8th for example, this means from July 8th at 6 am to July 9th at 5:59 am.

**RESULTS**

Weather stations recorded continuously from July 2nd until September 10th, 2013. Over this period, ten days met the conditions set for pavement-watering. Of the ten watered days, July 8th, 9th, 10th and 16th were the coolest ($T_x$≤30°C), with July 22nd, 23rd, August 1st and 2nd being the warmest ($T_x$≥35°C, $T_n$≥20°C). August 23rd and September 5th were also watered and had intermediate temperatures (35°C≥$T_x$≥30°C).

Several measurement interruptions occurred over this period. Rue du Louvre was most affected with its control station unoperational from July 19th until August 19th and from September 4th until September 10th. At Belleville, only one interruption occurred from the 22nd to the 25th of July. These events were poorly timed, resulting in the absence of control measurements on July 22nd and 23rd at either site and on August 1st and 2nd at the Louvre site.

It should therefore be kept in mind that results from rue du Louvre only include the coldest watered days, while July 22nd and 23rd are missing from the Belleville data.

**Effects on mean radiant temperature**

Figure 3 illustrates the difference between watered and control stations at the Louvre (top) and Belleville (bottom) sites for MRT. Deviations between the blue and red curves are statistically significant only if the blue curve is not between the dotted red lines.

As can be seen, both sites behave quite differently, with signal amplitudes ranging from [-2°C;4°C] at the Louvre site to [-6°C;10°C] at the Belleville site. 24-hour mean and maximum cooling effects are summarized in Table 3.

24-hour average and daily maximum effects are quite different between sites. Although a net cooling effect of 0.36°C is seen at the Louvre site, a warming of 0.09°C is seen at Belleville. However, the latter result is not statistically significant. No statistically significant 24-hour effect is therefore detected for Belleville, while a staticsally significant average cooling of 0.36°C is seen for Louvre.

When the hourly curves in Figure 3 are considered, the MRT difference curve is always lower on watered days than on dry days at the Louvre site. This is not the case at the Belleville site. However, the deviations between the control and watered day curves are not always statistically significant at either site. Overall, the effects are most often statistically significant at night and at the Louvre site. The maximum effects reported in Table 3 are statistically significant at both sites.

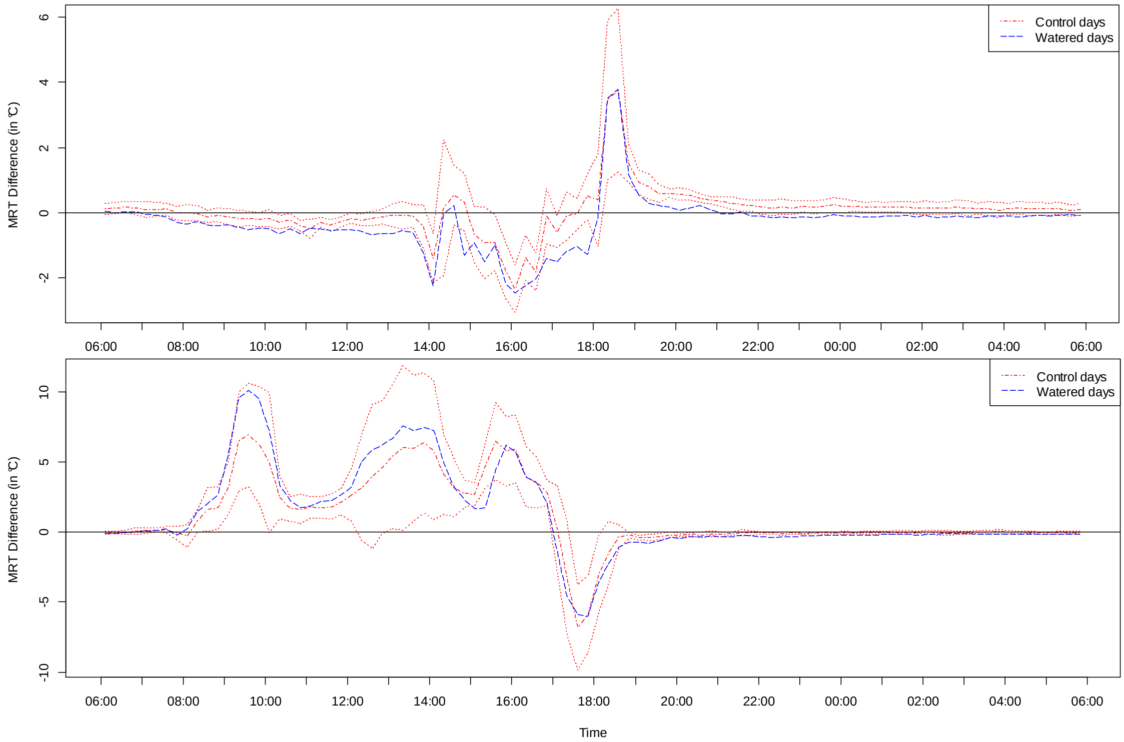


*Figure 3: Difference in mean radiant temperature between twin stations at the Louvre (top) and Belleville (bottom) sites. Solid lines indicate the mean value for control (red) and watered (blue) days, dotted red lines indicate the 95% confidence interval of the difference between the control and watered day mean curves.*

**Table 3: Mean and maximum cooling effects of pavement-watering on MRT at Louvre or Belleville**

| Site | Mean (24-hour) effect | Maximum effect |
|---|---|---|
| Louvre | 0.36°C | 1.79°C |
| Belleville | -0.09°C | 2.94°C |

**Effects on pedestrian thermal comfort**

Figure 4 illustrates the hourly difference between watered and control stations at the Louvre (top) and Belleville (bottom) sites for UTCI.

As was the case for MRT, both sites behave quite differently, despite reduced signal amplitudes compared to that of MRT with [-0.5°C;1.75°C] at Louvre and [-2°C;3.5°C] at Belleville. 24-hour mean and maximum cooling effects are summarized in Table 4.

Unlike for MRT, the effects on UTCI are relatively similar between sites. UTCI is reduced by an average of 0.21°C at the Louvre site and by 0.12°C at the Belleville site. However, only the effect on rue du Louvre is statistically significant. No statistically significant 24-hour effect on UTCI is therefore visible at the Belleville site.

When the hourly curves in Figure 4 are considered, statistically significant effects exist, although they are less numerous than for MRT. Maximum effects are significant and in the same order of magnitude, between 0.98°C and 1.20°C. As was the case for MRT, the hourly effects are most often significant at night and at the Louvre site.

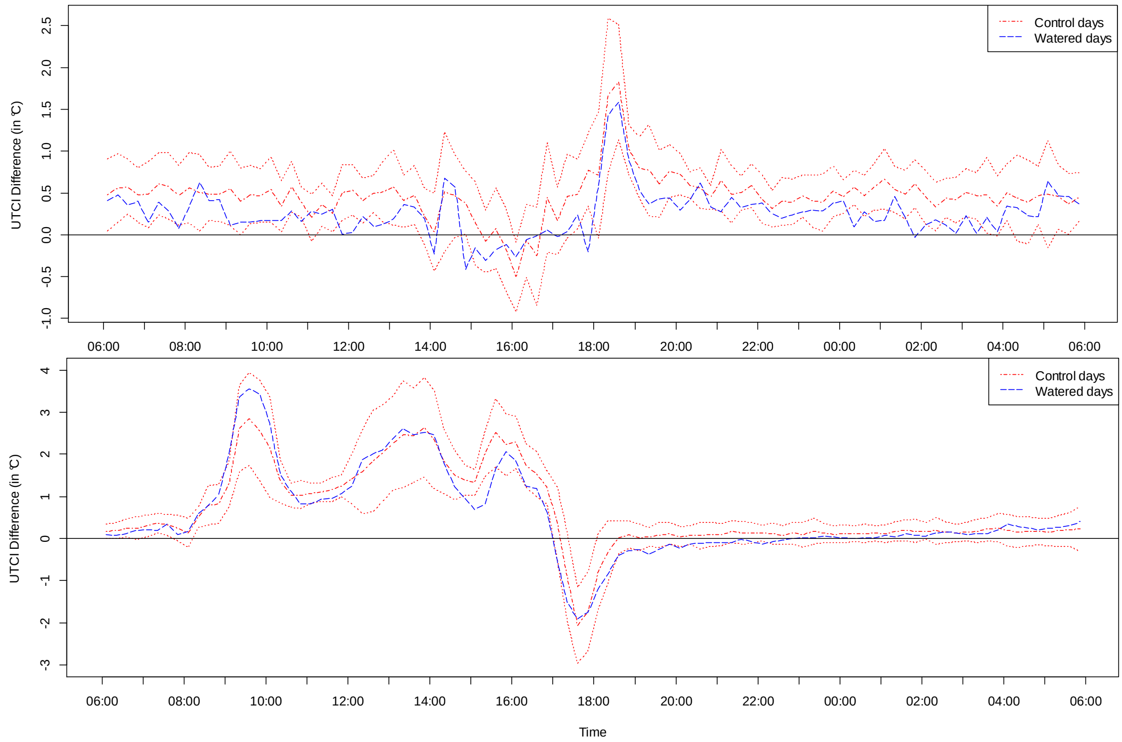


*Figure 4: Difference in UTCI between twin stations at the Louvre site (top) and at the Belleville site (bottom). The dashed lines indicate the mean value for control (short red dashes) and watered (long blue dashes) days, while red dotted lines indicate the 95% confidence interval of the difference between the control and watered day mean curves.*

**Table 4: Mean and maximum cooling effects of pavement-watering on UTCI at Louvre or Belleville**

| Site | Mean (24-hour) effect | Maximum effect |
|---|---|---|
| Louvre | 0.21°C | 0.98°C |
| Belleville | 0.12°C | 1.20°C |

## DISCUSSION

For both MRT and UTCI, 24-hour average effects are always greater at the Louvre site, while maximum effects are higher at the Belleville site. Furthermore, the 24-hour average effects site are only statistically significant at the Louvre site, while maximum effects are always significant regardless of the site considered. Finally, the hourly effects are most often significant at night and at the Louvre site. Maximum effects for MRT were in the order of a few degrees Centigrade while they were around one degree for UTCI. Overall, greater, more significant results were found for MRT than for UTCI.

On the one hand, the more significant and higher 24-hour results obtained at rue du Louvre are most likely explained by the proportion of street that is watered. While rue du Louvre was watered over 100% of its width, only a third of rue Lesage was watered.

On the other hand, the highest maximum effects were reached at the Belleville site. This may be linked to the absence of data on the hottest watered days for the Louvre site, when the effects are expected to be highest. However, it could also be linked to the Belleville site's orientation, since both site canyons have the same aspect ratio. For an aspect ratio of one, N-S streets experience similar conditions on either side of the street, while E-W streets have very different conditions between the North and South sidewalks, due to predominant daytime sunlight or shade, respectively. Maximum heat stress conditions are therefore much higher on the North side of an E-W street than on its South side or in a N-S street during the summer. These links between aspect ratio, orientation and pedestrian thermal comfort were studied by Ali-Toudert & Mayer (2006). Since it is expected that the effects are greatest in the hottest conditions, cooling may be increased by watering the North sidewalk rather than the pavement on rue Lesage. However, because of the missing data at the Louvre site, this cannot be confirmed. Finally, the difference in paving materials may also explain some of these aspects.

We now look to evaluate the health or comfort impacts of these effects. No universal relation with mortality risk has been established for MRT at this time to our knowledge, while UTCI is scaled according to five heat stress levels for hot environments. To evaluate the effect of pavement-watering on pedestrian thermal comfort through UTCI, we must therefore compare the effect with the span of the UTCI heat stress categories, i.e. between 6° and 8°C. With a maximum cooling effect of 1.2°C, pavement-watering has a limited effect on pedestrian thermal comfort, only rarely causing a downwards shift in heat stress category. However, it should be noted that pavement-watering performs well in comparison to other urban surface cooling methods, such as high-albedo pavement materials (Erell, Pearlmutter, Boneh, & Kutiel, 2013).

## CONCLUSIONS

The effects of pavement-watering on pedestrian thermal comfort were evaluated via MRT and UTCI, using data collected during a field experiment of pavement-watering conducted at two sites in Paris, France over the summer of 2013. The N-S site was entirely watered, while only the pavement, corresponding to a third of total width, of the E-W site was watered.

For both MRT and UTCI, average cooling effects were highest at the N-S site, reaching 0.36°C for MRT and 0.21°C for UTCI, while maximum cooling was highest at the E-W site, with up to 2.9°C for MRT and 1.2°C for UTCI. Average cooling at the E-W site was not statistically significant, while maximum cooling was significant at both sites.

The higher effect reached at the Belleville site may be closely tied to the street's orientation, but further measurements would be necessary to confirm this. If this is the case, it may be more efficient to water the North sidewalk of E-W streets rather than their pavement.

To our knowledge, no tools currently exist to evaluate the health impact of observed MRT cooling. It is therefore not yet possible to estimate the health impacts of pavement-watering with MRT. In terms of UTCI, observed cooling was found to be limited in comparison to the level necessary to obtain a downwards shift in heat stress category. Regardless, the method performs better than others such as high-albedo pavement materials.

In order to continue to evaluate pavement-watering against other methods such as urban greening or artificial shading, further studies such as that conducted by Shashua-Bar, Pearlmutter, & Erell (2011) should be conducted in the Parisian urban environment. Trials should take all relevant decision-making factors into account, including the cost, water consumption and feasibility of each method.

## NOMENCLATURE

*BMI* = biometeorological index [°C]

*MRT* = mean radiant temperature [°C]

$T_n$ = minimum daily temperature [°C]

$T_x$ = maximum daily temperature [°C]

*UTCI* = universal thermal climate index [°C]

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