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Martin Hendel, Pierre Gutierrez, Morgane Colombert, Youssef Diab, Laurent Royon. Measuring the Effects of Urban Heat Island Mitigation Techniques in the Field: an Application to the Case of Pavement-Watering in Paris. 2015. hal-01113917v1

HAL Id: hal-01113917

<https://hal.science/hal-01113917v1>

Preprint submitted on 10 Feb 2015 (v1), last revised 2 Mar 2016 (v4)

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Measuring the Effects of Urban Heat Island Mitigation Techniques in the Field: an Application to the Case of Pavement-Watering in Paris

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ABSTRACT

Urban heat island (UHI) countermeasures are of growing interest for cities. Field studies of micro-climatic effects of such countermeasures are scarce, yet are essential to properly evaluate the effectiveness of anti-UHI policies. One measure which has been thoroughly studied in the field is pavement-watering. The standard approach to quantifying its micro-climatic effects is to focus on the difference in measurements made at case and control stations, tacitly assuming that under normal conditions measurements made at both sites are equal.

A field study of pavement-watering was conducted in Paris, France over the summers of 2013 and 2014 at two sites, one watered over its whole width and the other only over one third. Analysis of the field measurements of 1.5- and 4-m air temperature and relative humidity, mean radiant and UTCI-equivalent temperature reveal that the assumption of null interstation differences is unfounded. The standard approach is therefore ill suited to evaluate pavement-watering effects.

An approach based on a two-sample t-test of the difference between watered and reference day interstation means was conducted. In the case of full-street-width watering, pavement-watering effects had statistically significant daily effects, while only 1.5-m relative humidity was significantly affected in the case of one-third-street-width watering. Watering was found to reduce maximum daily heat stress, while having smaller-amplitude statistically significant effects at night, thus slightly reducing UHI intensity. Statistically significant effects occurred most often at night for all parameters except relative humidity, which was most affected during the day. The greatest effects were reached during the day for all parameters with reductions of 0.79°C, 1.76°C and 1.03°C for air, mean radiant and UTCI-equivalent temperatures and a 4.1% increase in relative humidity.

The methodology developed is not specific to pavement-watering and can be applied to the field evaluation of any UHI countermeasure.

1. Introduction

Countermeasures to the urban heat island (UHI) effect are of growing interest to decision makers. Certain measures have been encouraged or made mandatory for new buildings through local legislation or regulation, such as California's Title 24 in the case of cool roofs [1]. Such policies are supported by the growing scientific literature on the topic of UHI countermeasures.

Cool materials, which can be reflective, permeable or covered with low vegetation such as grass, have been thoroughly studied in the lab or on small-scale prototypes [2]–[7]. Results indicate that surface temperatures are significantly reduced compared to standard materials, thus reducing atmospheric warming. Equivalent work on green spaces usually focuses on existing

parks [8], [9], but smaller scale testing has also been conducted [10]. Parks have been found to be up to a few degrees cooler than their surroundings through the effects of evapotranspiration and shading. However, field evaluations and monitoring of large-scale implementation of cool materials or new urban green spaces are scarce [11], [12].

Actual measurements of the atmospheric effects of UHI countermeasures are of great importance to the scientific community, to help validate simulation models for instance, but also for decision-makers. There is a need on behalf of the latter group to be able to evaluate the effectiveness of anti-UHI policies, namely via in-situ micro-climatic measurements.

To date, large-scale micro-climatic effects are often studied with the help of computer simulations [13]–[15]. Understandably, very few experimental studies of cool materials include micro-climatic effects since this would require large-scale implementations in order to ensure that atmospheric effects are detectable.

Interestingly, pavement-watering has been studied in the field via several independent studies. Japan began work in the 1990's with the use of preexisting pavement-watering installations in Nagaoka City or block-scale demonstrators in Tokyo [16]–[19]. More recently, field studies have been conducted in Paris or Lyons in France with the use of cleaning trucks or prototypes of permanent watering infrastructure [20], [21]. In all of these cases, the methodology applied is a direct comparison between case and control measurements, the observed interstation difference being interpreted as the effect of pavement-watering. Among UHI countermeasures, pavement-watering has the advantage of being reversible, thus permitting the study of the test site in its pre-implementation state. This is obviously not the case of cool or green surfaces which have lifetimes of several years.

This paper uses a pavement-watering experiment conducted in Paris, France during the summers of 2013 and 2014 as an example to propose a methodology to measure the field effects of UHI countermeasures. This experiment has already been analyzed by the authors to optimize the water consumption and frequency of pavement-watering [22], [23]. In the process, further light will be shed on the effects of pavement-watering on micro-climatic parameters and pedestrian thermal comfort in the field. Through this case study, we will demonstrate that the frequently-seen direct case-control comparison is not suited to dense urban environments and we will propose the use of statistical analysis tools. Focus will be set on the methodological difficulties encountered during the analysis of collected data and the alternatives developed by the authors to overcome them. The resulting methodology can be generalized to all UHI countermeasures if sufficient time is available to study the micro-climatic conditions present before the countermeasure is put into place.

2. Materials and methods

2.1 Site selection

Two sites in Paris, France were investigated over the summers of 2013 and 2014. Local micro-climatic data was measured on the rue du Louvre, located on the border of the 1st and 2nd Arrondissements, and in the 20th Arrondissement. Both sites will be respectively referred to as the Louvre and Belleville sites hereafter. 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.

In order to filter out the role of other factors and facilitate the detection of the pavement-watering effect, each pair was selected according to strict criteria. These included a minimum

distance between stations (10 times street width at least), minimal immediate presence of vegetation, identical street orientations, canyon aspect ratios and street widths. Pairs were also chosen so that the urban materials around them, e.g. roads or building façades, were as similar as possible. Road traffic, surrounding parks and vegetation, station shading and topography were also controlled for.

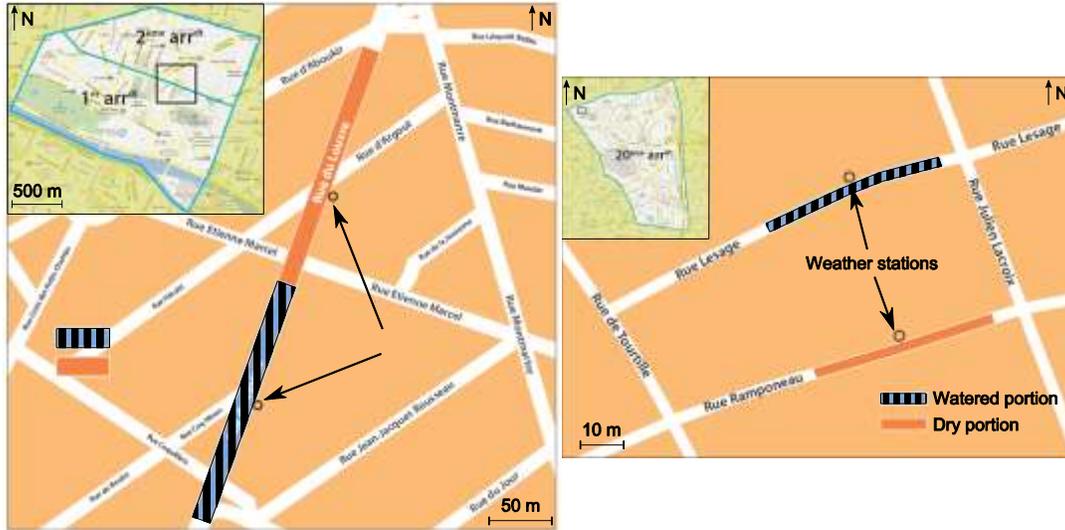


Figure 1: Map of weather station positions at the Louvre (left, from [22]) and Belleville (right) sites

Louvre stations are positioned approximately 200 meters apart in the same street, while they were positioned in two parallel streets, rue Lesage and rue Ramponeau, at the Belleville site. In terms of road materials, impervious asphalt concrete approximately 16 cm deep is laid on a 16-cm cement-treated base at the Louvre stations. At the Belleville stations, different cobblestones are used at the watered and control sites, with sandstone pavers at the case and granite pavers at the control.

Rue du Louvre, rue Lesage and rue Ramponeau have an aspect ratio approximately equal to one ($H/W=1$). Rue du Louvre has an approximate N-S orientation, while at Belleville both streets have a roughly E-W orientation.

As an indication of the resulting match between stations, Figure 2 compares solar irradiance measurements at the case and control stations for Louvre and Belleville on July 14th, 2013.

While solar irradiance measurements at the Louvre stations are highly consistent with each other, significant differences are visible between the Belleville stations, occurring from 9 am to 2 pm and from 5 pm to 6 pm. One contributor to the differences at Belleville is a street sign directly South of the control station which shaded the black globe thermometer a few hours a day at midday over this period. This sign was supposed to have been removed after station installation but in reality never was.

Overall, the match between stations is much better for Louvre than for Belleville.

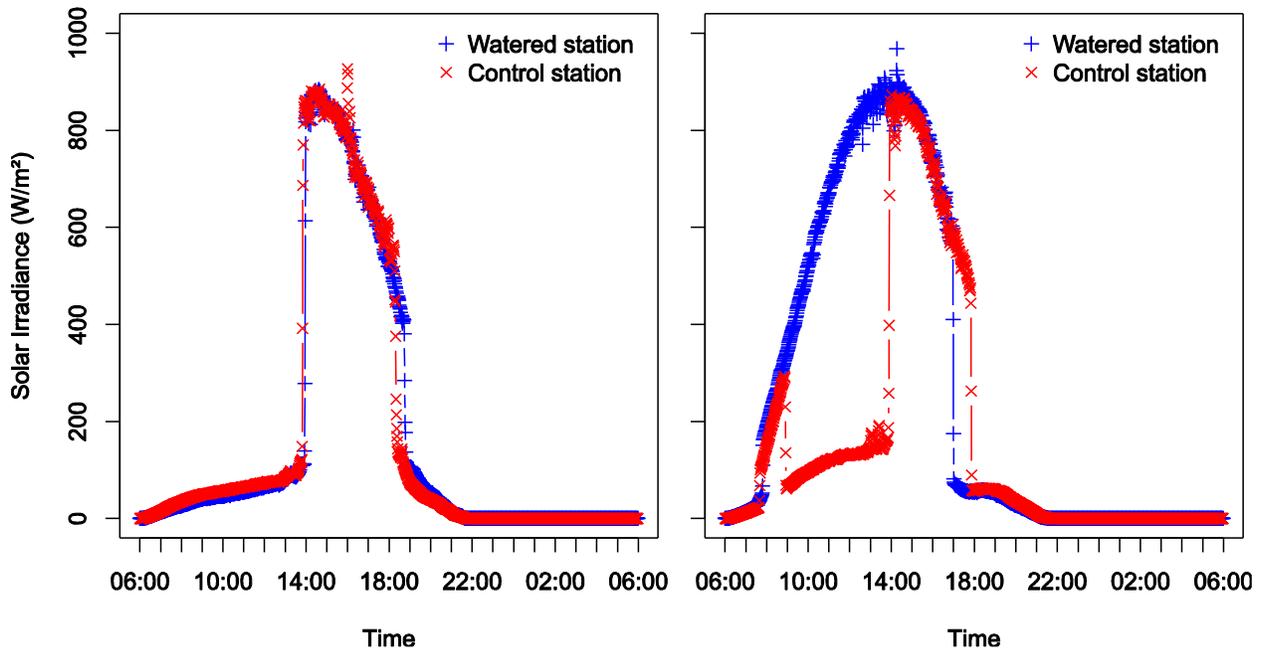


Figure 2: Solar irradiance at Louvre (left) and Belleville (right) on July 14th, 2013.

2.2 Instruments

Weather station design is presented in Figure 3 for rue du Louvre. Instruments within pedestrian reach were protected behind a cylindrical white-painted steel cage. Black globe temperature (T_g), air temperature (T_a) and wind speed (v) measurements from the weather station were used to estimate mean radiant temperature (MRT) following the ASHRAE method [24]. Table 1 summarizes the instruments used for this analysis as well as their measurement height and accuracy. All measurements were recorded continuously every minute and are presented in local daylight savings time (UTC +2).

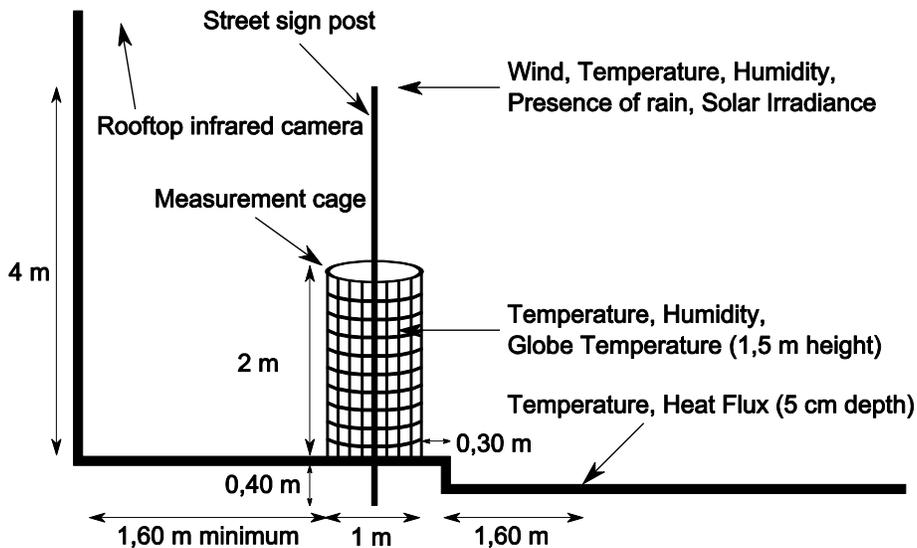


Figure 3: Weather station design and instrumentation (rue du Louvre)

Table 1: Instrument type, measurement height and accuracy

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

Universal Thermal Climate Index (UTCI) was also calculated from these measurements for each station to estimate pedestrian thermal comfort [25]. 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.

We fast-calculated UTCI equivalent temperature with the FORTRAN code written by Peter Bröde in 2009 which we 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 speeds, respectively, as well by globe temperature being measured inside the cylindrical cage which unavoidably shades the instrument.

For the upcoming analyses, the one-minute data series are smoothed with a ten-minute moving average.

2.3 Watering method

The watering method applied to the Louvre site is that described by Hendel et al. [22]. Namely, 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 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 temperatures.

Table 2: Weather conditions required for pavement-watering and heat wave warnings [22]

Parameter	Pavement-watering	Heat-wave warning level
T_n	$BMI_{Min} \geq 16^\circ\text{C}$	$\geq 21^\circ\text{C}$ for three consecutive days
T_x	$BMI_{Max} \geq 25^\circ\text{C}$	$\geq 31^\circ\text{C}$ for three consecutive days
v	≤ 10 km/h	-
Sky conditions	Sunny (less than 2 oktas cloud cover)	-

On rue du Louvre, cleaning trucks were used to sprinkle approximately 1 mm every hour from 6:30 am to 11:30 am and every 30 minutes from 2 pm until 6:30 pm on the sidewalk and pavement. Both watered and dry portions of the street are approximately 180 m long and 20 m wide.

At Belleville, a removable 40-m watering pipe was laid along the gutter to water the cobblestone pavement on rue Lesage continuously from 7 am to 7 pm across its 4 meter width. Water use at the Belleville site was approximately 25 mm/h. In terms of the watered surface ratio, rue du Louvre was 100% watered, while rue Lesage was approximately 33% watered. The watering process is illustrated for both sites in Figure 4.



Figure 4: Watering on rue du Louvre (left, from [23]) and rue Lesage (right)

Water used for this experiment was supplied by the city's 1,600-km non-potable water network, principally sourced from the Ourcq Canal. Although water temperature was not measured, its typical summertime range is 20°-25°C.

2.4 Interpretation method

As described in the Introduction, the standard method used in previous work on pavement-watering is to interpret its effect on each discussed micro-climatic parameter as the difference between measurements from two stations or areas: one experimental, i.e. watered, and one control, i.e. unwatered [16]–[21]. In doing so, the hypothesis is implicitly made that under normal conditions without pavement-watering, the difference between station measurements should be constant and equal to zero. It should be noted however that Kinouchi and Kanda do point out that microclimatic conditions were either equal on average or were warmer and drier at the watered site a few hours before and after pavement-watering [16]. This assessment was not investigated further in their analysis of pavement-watering effects.

We adopt the same approach for our own microclimatic measurements. In addition to assuming that measurements at each station should be equal on days without watering, we include the condition that considered days be of Pasquill atmospheric stability class A or A-B [26]. This condition requires insolation to be high (i.e. clear or very low cloud cover) and wind speeds to be low (less than 3 m/s). This condition improves the comparability of days with and without watering by limiting the differences in weather conditions.

Unless otherwise specified, the following analyses focus on the difference between case and control stations, calculated in the following fashion: $y_{difference} = y_{watered} - y_{control}$. Therefore, negative values indicate that the watered station parameter is lower than that of the control

station, and vice versa. The difference between case and control measurements will be referred to as the interstation difference.

Finally, as stated in the Introduction, pavement-watering has the advantage over other UHI countermeasures of being fully reversible, i.e. watering can be conveniently turned on or off without modifying the preexisting conditions. Indeed, most UHI countermeasures are meant to be permanent and it is very difficult if not impossible to revert back to the preexisting state. Therefore, with pavement-watering it is possible to easily compare reference days, i.e. those without watering, with case days, i.e. those with watering, referred to hereafter as watered days.

For better comparability between reference and watered days, the discussed daily time series will begin at 6 am and end at 5:59 am the following day. Thus, data from July 8th refers to data collected between July 8th at 6 am and July 9th at 5:59 am.

3. Results and discussion

Over the summer of 2013, ten days met the weather conditions required for pavement-watering and 23 additional ones could be used as reference days. Of the ten watered days, July 8th-10th and 16th were the coolest ($T_x \approx 30^\circ\text{C}$), with July 22nd, 23rd and August 1st and 2nd being the warmest ($T_x \geq 35^\circ\text{C}$, $T_n \geq 20^\circ\text{C}$). August 23rd and September 5th were also watered and had intermediate temperatures ($35^\circ\text{C} \geq T_x \geq 30^\circ\text{C}$). Over this period, the control station on rue du Louvre was vandalized and thus unoperational from July 19th to August 19th and from September 4th until the end of the summer. Over the same period, the Belleville control station was unpowered from 4 pm on July 22nd until 5 pm on July 25th.

Although 2014 is France's warmest years since the 1900's as of this writing [27], only two days met the required weather conditions for pavement-watering over the summer of 2014 and five could be used as reference days. July 17th and 18th are the two watered days. August 2014 was particularly cool with a monthly temperature approximately 1.5°C colder than average [28]. Although no events caused any of the stations to fail during the summer of 2014, road work occurred at the Louvre watered station from July 29th until the end of the summer.

We begin by presenting the difference profiles for measured parameters at Louvre and Belleville from July 2nd to July 19th 2013. The analyses will be conducted over the full extent of the summers of 2013 and 2014.

3.1 Direct comparison between case and control stations

Figure 5 presents the difference curves between the case and control stations for air temperature and relative humidity at 1.5 m and 4 m, and mean radiant temperature and UTCI, for rue du Louvre between July 2nd and July 18th. Figure 6 shows the same curves for Belleville.

Judging solely by the reference days (red), it is immediately apparent that the assumption that measurements at twin stations are constant or equal is unfounded. The differences in insolation at the Belleville site revealed that those stations were imperfectly matched. It is therefore not surprising for significant differences to exist between the Belleville stations. However, insolation at the Louvre stations was close to identical and thus differences of the amplitude seen in Figure 5 are unexpected.

Even after smoothing the data, filtering meteorological conditions and selecting station positions as similar as possible, measurements at paired stations cannot be considered to be equal, even up to a constant, no matter which parameter is considered at 1.5 or 4 m a.g.l. Moreover, the data exhibits variation from one reference day to the next.

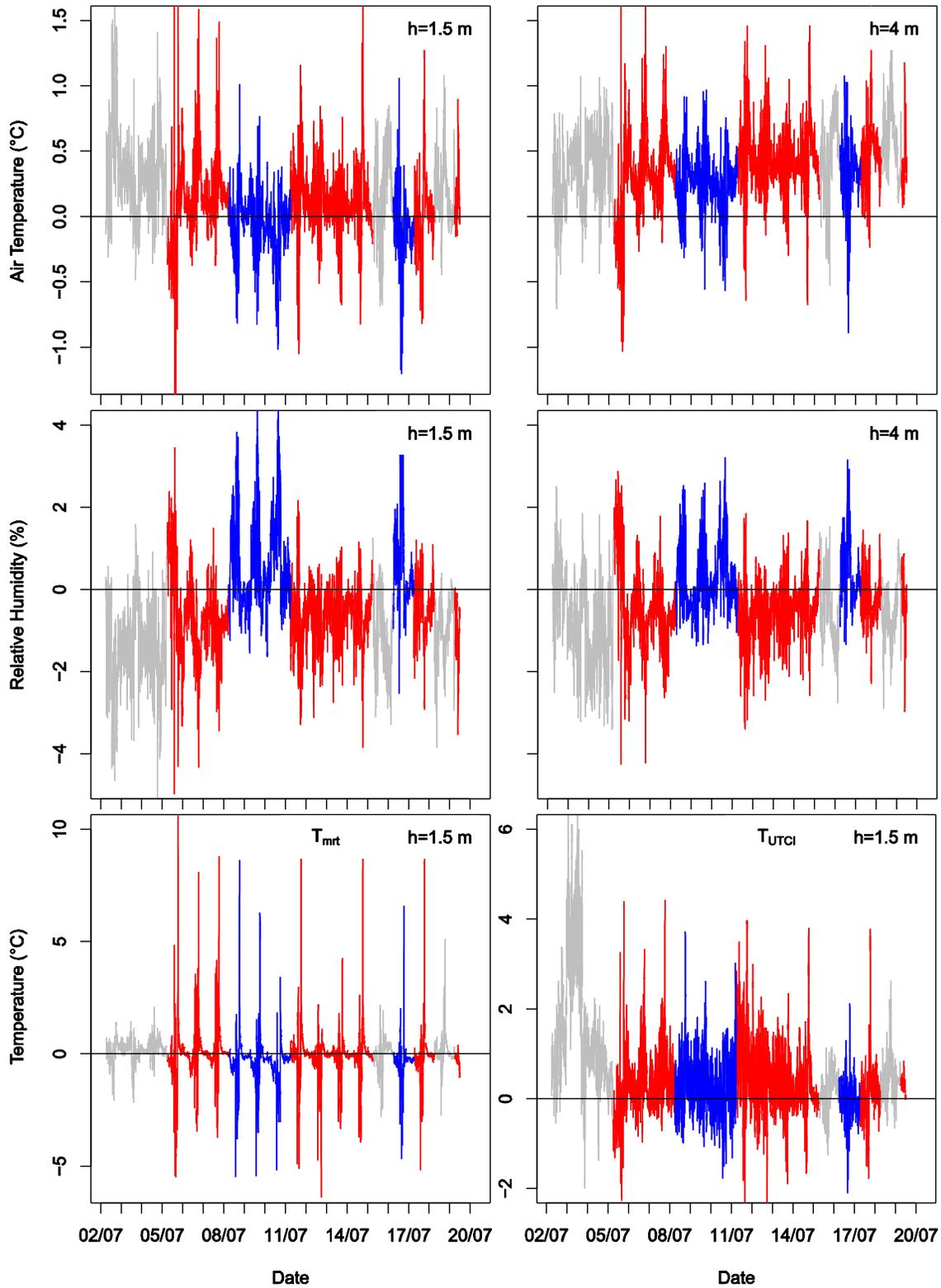


Figure 5: Differences between Louvre case and control stations from July 2nd to 19th, 2013 (top to bottom) for T_a and RH at 1.5 m (left) and 4 m (right) height and MRT (bottom left) and UTCI (bottom right). Watered days are in blue, dry (reference) days are in red. Days with uncomparable weather conditions are in grey.

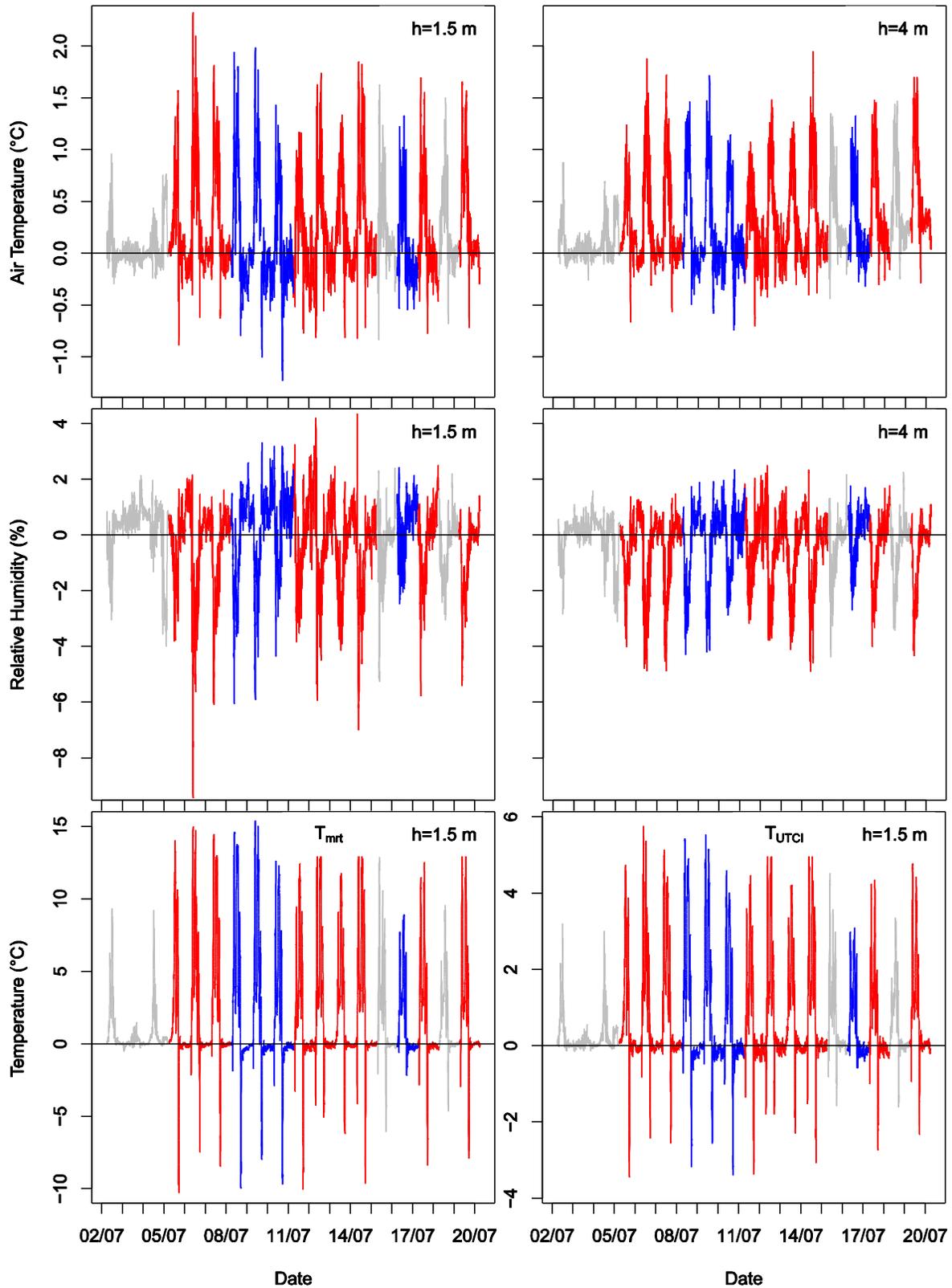


Figure 6: Differences between Belleville case and control stations from July 2nd to 19th, 2013 (top to bottom) for T_a and RH at 1.5 m (left) and 4 m (right) height and MRT (bottom left) and UTCI (bottom right). Watered days are in blue, dry (reference) days are in red. Days with uncomparable weather conditions are in grey.

Studying these curves does however provide insight into the relative behavior of the paired stations. Table 3 summarizes the mean differences observed on reference days for each parameter, height and site over the summers of 2013 and 2014.

Table 3: Average case-control difference on reference days over the summers of 2013 and 2014.

Parameter	Height	Louvre	Belleville
Air temperature	1.5 m	+0.26°C	+0.21°C
	4 m	+0.40°C	+0.31°C
Relative humidity	1.5 m	-0.99%	-0.40%
	4 m	-0.81%	-0.56%
MRT	1.5 m	-0.13°C	+1.35°C
UTCI	1.5 m	+0.52°C	+0.72°C

On reference days air temperatures at 1.5 m and 4 m are generally higher at the case station than at the control station while relative humidity is generally lower for both Louvre and Belleville. The average air temperature differences, in the order of a few tenths of a degree Celsius, are increased at both sites at 4 meters relatively to 1.5 meters. MRT difference curves exhibit high amplitudes during periods of direct insolation (see Figure 2 for details), reaching up to 15°C at Belleville and 10°C at Louvre. This is due to the high influence of insolation on MRT. Even short-lasting differences in insolation between stations due to a passing cloud for example can cause high amplitude differences in MRT. Finally, UTCI is warmer at the case station for both sites. On average, the case station is therefore warmer and drier than the control station at both sites and paired station measurements are not equal on reference days.

The low average difference in MRT between the Louvre stations vouches for the good match in shading conditions between them. This is not the case for the Belleville site where the case station is significantly more insolated than the control as seen in Figure 2.

As can be seen by comparing the MRT and UTCI curves for Belleville, the difference in MRT is the main driver for the UTCI difference during insolation. This is consistent with the sensitivity analyses conducted by Bröde et al., i.e. that for air temperatures higher than 20°C, UTCI equivalent temperature increases by about 3°C for every 10°C increase in MRT [29].

It should be noted that in the absence of measurements on reference days, this may not have been detected and the effects of pavement-watering may well have been deemed absent or even counter-productive. This leads to our first recommendation for field assessments of UHI countermeasures: characterize the sites where the countermeasure is planned prior to implementation.

It is therefore necessary for us to adapt the original approach. Although direct comparisons between case and control weather stations may be valid in certain situations, it is unlikely that this is the general case, especially in dense urban environments which are quite complex. We therefore argue that direct case-control comparison is not a valid method to determine the field effects of UHI countermeasures in cities.

3.2 Comparing interstation behavior on reference and watered days

In the previous section we demonstrated that UHI countermeasures effects cannot be detected by direct comparisons between case and control stations in cities. We now propose a method based on comparisons of interstation differences on days with and without watering.

3.2.1 24-hour average differences

As a first approach, the average differences observed on reference days will be compared with those observed on watered days. If pavement-watering effects do exist, a variation in the average interstation difference should occur on watered days compared to reference days. The daily-averaged interstation differences on watered days and their variation compared to reference days are reported in Table 4.

Table 4: Average case-control difference on watered days and variation from reference days over the summers of 2013 and 2014.

Parameter	Height	Watered days		Variation	
		Louvre	Belleville	Louvre	Belleville
Air temperature	1.5 m	0.01°C	+0.15°C	-0.25°C	-0.06°C
	4 m	+0.26°C	+0.31°C	-0.14°C	+0.00°C
Relative humidity	1.5 m	+0.47%	-0.10%	+1.46%	+0.29%
	4 m	+0.11%	-0.47%	+0.93%	+0.09%
MRT	1.5 m	-0.27°C	+1.67°C	-0.40°C	+0.32°C
UTCI	1.5 m	+0.22°C	+0.68°C	-0.29°C	-0.04°C

The average case-control differences are lower for each parameter on watered days compared to reference days at Louvre, except for relative humidity which is increased. T_a and UTCI are reduced in the order of 0.1°C, MRT is reduced by a few tenths of a degree Celsius, while RH is increased by about one percentage point at Louvre. Similar changes occur at Belleville except that 4-m air temperature is unchanged and MRT is increased by 0.32°C.

The changes in case-control differences are indicative of pavement-watering effects. At first glance, it seems that pavement-watering reduces air and UTCI temperatures and increases relative humidity over 24 hours, while MRT effects are contradictory between Louvre and Belleville.

A two-sample t-test is now used to analyze the 10-minute data series.

3.2.2 10-minute data: statistical approach

First, the average interstation profile is established for reference and watered days. Respectively, all reference and watered day observations are grouped by time of day by the minute. For example, each observation made at 2:07 pm on reference days are grouped together, forming a sample of reference day observations made of 2:07 pm. 1,440 such samples are thus obtained for both reference and watered days. The interstation difference is then compared minute-by-minute on watered and control days.

A two-sample t-test is conducted for each minute-by-minute difference between the mean value at the i -th minute (μ_i) on watered and reference days of the interstation difference. The null hypothesis (H_0^i) chosen states that μ_i is greater on watered days than on reference days. The alternative hypothesis (H_a^i) states that μ_i is strictly lower on watered days than on reference days. These hypotheses constitute a one-tailed test. For this analysis, the opposite of RH and RH^{4m} will be used in order to avoid reformulating the hypotheses for these two parameters. Both hypotheses can be summarized as follows, for $i \in 1; 1440$:

$$H_0^i: \mu_i^{wet} - \mu_i^{dry} \geq 0 \quad (1)$$

$$H_a^i: \mu_i^{wet} - \mu_i^{dry} < 0 \quad (2)$$

A significance level of 0.05 is used. Using the field data, a two-sample t-test of the null hypothesis is conducted. If the obtained p-value is lower than the significance level of 0.05, then the null hypothesis is rejected.

If this method is applied with a significance level of 0.01 to the daily interstation differences, the following is apparent

Figure 7 and Figure 8 plot the average change detected on watered days compared to reference days (solid blue line) for the Louvre and Belleville sites, respectively. The x-axis represents no difference between watered and reference days. The confidence interval is illustrated by the two red dashed curves. If the solid curve is in between the dashed curves, then the average effect at that time of day is not statistically significant.

Watered days exhibit mostly negative changes in T_a , T_a^{4m} , MRT and UTCI and mostly positive ones for RH and RH^{4m} . In other words, the environment around the case stations is cooler and more humid, yet overall more comfortable, on watered days than on reference days. Evidently, watering is more effective at Louvre than at Belleville.

Taking a closer look, it appears that the greatest effects occur in the afternoon between 2 pm and 7 pm for all parameters, during pavement insolation. Of all considered parameters, RH is the one that best reflects watering events. Indeed, changes in RH at Louvre are simultaneous to watering which occurs from 6:30 am and 6:30 pm with an interruption between 11:30 am and 2 pm. This is not as clear at Belleville, with continuous watering from 7 am to 7 pm.

Although effects are greater at Louvre than at Belleville, maximum effects are comparable and occur in the afternoon for all parameters. The higher average effects at Louvre, already detectable with daily effects briefly described in the previous section, are attributed to the difference in watering strategies between sites, i.e. 100% at Louvre is more effective than 33% watering at Belleville.

While average effects positively affect weather conditions, they are not always statistically significant. Table 5 and Table 6 summarize the duration of statistically significant effects as well as the mean and maximum values reached during that time for air temperature, relative humidity, MRT and UTCI for both sites.

Overall, watering effects are more often statistically significant at Louvre, in addition to greater average effects. Looking at the temporal distribution of significant effects, it appears that both for Louvre and Belleville they occur most often at night (after 6 pm) for T_a , T_a^{4m} , MRT and UTCI and most often during the day for RH and RH^{4m} .

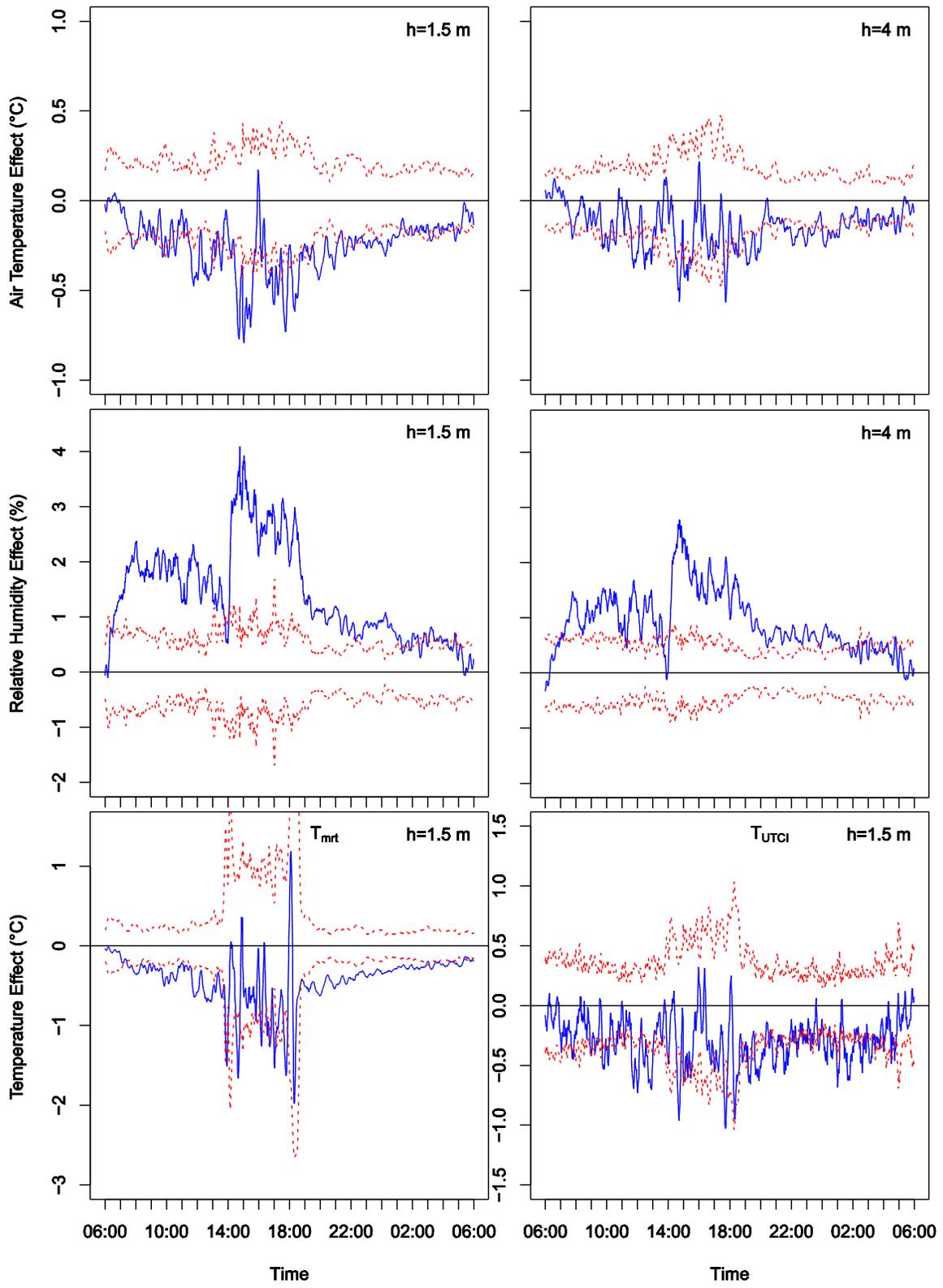


Figure 7: Average watering effect at Louvre over the summers of 2013 and 2014 (top to bottom) for T_a and RH at 1.5 m (left) and 4 m (right) height and MRT (bottom left) and UTCI (bottom right). Average effects are solid blue, confidence intervals are dashed red.

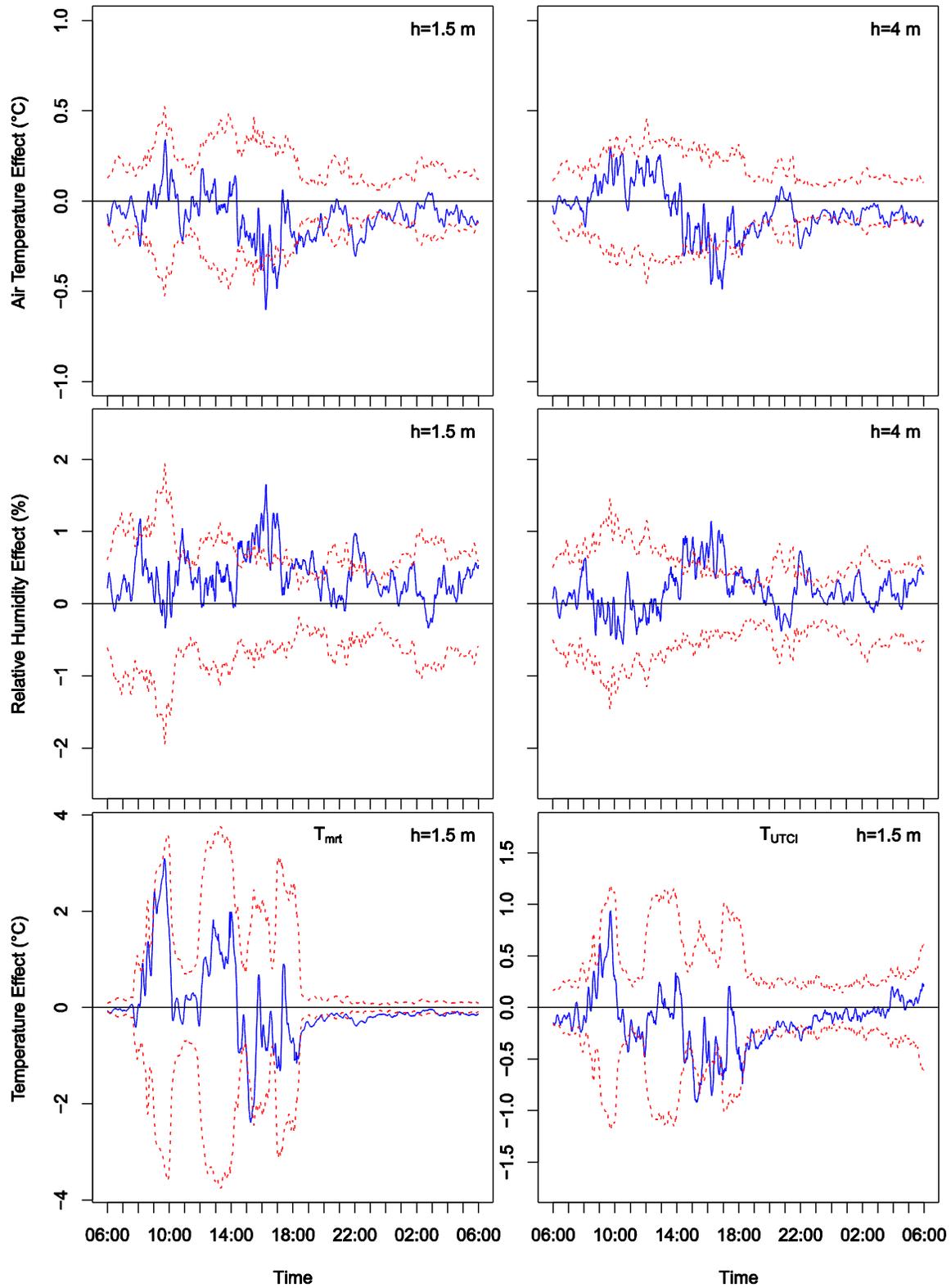


Figure 8: Average watering effect at Belleville over the summers of 2013 and 2014 (top to bottom) for T_a and RH at 1.5 m (left) and 4 m (right) height and MRT (bottom left) and UTCI (bottom right). Average effects are solid blue, confidence intervals are dashed red.

Table 5: Duration, mean and maximum values of statistically significant effects for Louvre over the summers of 2013 and 2014

Parameter	Height	Duration (hours/day)	Mean effect	Maximum effect
Air temperature	1.5 m	16.7	-0.31°C	-0.79°C
	4 m	12.2	-0.22°C	-0.57°C
Relative humidity	1.5 m	22.0	+1.5%RH	+4.1%RH
	4 m	20.3	+1.1%RH	+2.8%RH
MRT	1.5 m	19.5	-0.43°C	-1.67°C
UTCI		12.2	-0.42°C	-1.03°C

Table 6: Duration, mean and maximum values of statistically significant effects for Belleville over the summers of 2013 and 2014

Parameter	Height	Duration (hours/day)	Mean effect	Maximum effect
Air temperature	1.5 m	7.0	-0.21°C	-0.60°C
	4 m	7.0	-0.19°C	-0.49°C
Relative humidity	1.5 m	7.6	+0.7%RH	+1.6%RH
	4 m	5.2	+0.6%RH	+1.1%RH
MRT	1.5 m	10.5	-0.29°C	-2.39°C
UTCI		6.3	-0.39°C	-0.92°C

At Louvre, air temperature effects start to become statistically significant after 8 am and mostly remain so until 2 am. For RH, statistically significant effects occur practically as soon as watering starts at 6:30 am and remains so until 4 am, with a few minor interruptions, particularly during the watering interruption at midday. MRT effects are statistically significant as early as 7:30 am until 2 pm and from 6:30 pm until 6 am the next day. Statistically significant effects do occur in the afternoon but are more sporadic than in the morning or at night. UTCI statistically significant effects are more sporadic and mainly occur between 9:30 am and 3 am the next day.

Effects at Belleville are statistically significant much less frequently than at Louvre. For air temperature and relative humidity, they mainly occur between 3 pm and 5 pm and between 2 am and 3 am. For MRT they can be mostly found between 5:30 pm and 2 am. Finally, UTCI statistically significant effects are sporadically spread out between 11 am and 9 pm.

Pavement-watering therefore has statistically significant cooling effects up to several hours after watering has ended, although maximum effects occur in the afternoon when conditions are warmest and driest. Watering was also found to have significant effects up to 4-m above ground level on air temperature and humidity. Furthermore, the comparison between Louvre and Belleville shows that pavement-watering should target the largest possible portion of street width in order to best improve pedestrian thermal comfort.

3.3 Discussion

Our findings support that pavement-watering is an effective method for limiting maximum daily heat stress, while having statistically significant, although limited, UHI-reducing potential. Maximum effects reached up to 0.79°C and 0.57°C reductions in air temperatures at 1.5- and 4-m a.g.l., up to 4.1%RH and 2.8%RH increases in 1.5- and 4-m relative humidity, and up to 2.39°C and 1.0°C reductions in MRT and UTCI, respectively.

As pointed out in section 3.1, pavement-watering effects could not be determined by direct comparison of paired station measurements. We believe this is not an isolated occurrence, but is attributable to the intrinsic complexity of urban environments. We therefore recommend that field studies of UHI-countermeasures base their analysis on the comparison of reference periods, prior to implementation, with case periods, after implementation. By detecting preexisting interstation behavior, normal differences between sites will not be misinterpreted as UHI mitigation effects. While none of the field experiments of pavement-watering we found in the literature proceed in this fashion, it is noteworthy that numerical simulation studies naturally use this method. Indeed, they typically compare the same site in identical conditions, apart from the implementation of the UHI countermeasure.

We now compare our findings with those from numerical studies. Good agreement with Météo-France & CSTB is found if the difference in scale is taken into account, i.e. city-wide watering vs. watering a single street portion [15]. Indeed, they report maximum 2-m air temperature cooling of up to 2°C and UHI mitigation of up to 0.25-0.5°C at 6 am. Other simulation work at the district-scale conducted by Wei and He also agrees well with our findings with maximum reductions in MRT reaching 2.7°C in similar situations to our own (see their passage i-j) [30]. Air temperature, relative humidity or thermal comfort effects were not investigated. Kubo et al. also conduct a district-scale simulation and find maximum reductions of 0.73°C for 1.5-m air temperature, very similar to our own, and 2.13°C at a height of 0.5-m [4].

Despite the differences in methodology, findings from previous field work generally show good agreement with our own. In Paris in 2012, Bouvier et al. report up to 0.4°C cooling of 2-m air temperature and 4% increase in relative humidity for a single nighttime watering event [20]. In Lyon, Maillard et al. find a 0.5°C reduction in 1.5-m WBGT in the afternoon. In Nagaoka, Japan, Kinouchi & Kanda report reductions of up to 1°C in 1-m air temperature and 4°C in 1-m globe temperature as well as a 4% increase in relative humidity [16]. Average effects are in the order of 0.5°C for air temperature, 2°C for globe temperature and 3% for relative humidity. Also in Nagaoka, Takahashi et al. investigate 0.9-m air temperature cooling of up to 2°C in the morning and 4°C in the afternoon [18]. Finally, in Tokyo Yamagata et al. find up to 3°C and 2°C reductions in 0.5-m air temperature and WBGT, respectively [19].

Among these papers, Takahashi et al.'s findings exhibit the greatest difference with our own. Part of the difference is attributable to their lower measurement height, as proximity to the watered surface is expected to increase the detected effect. However, the difference in findings is substantial nevertheless. It may be the case that their watered area is naturally cooler than their control area even without watering. As no information on this possibility is provided, it is not possible to investigate it further. This goes for the other field works as well where natural background differences between chosen case and control sites may cause over- or underestimation of reported cooling effects.

The method can also be applied to the 24-hour differences initially reported in Table 3 and Table 4. Using the daily-averaged field data, two-sample t-tests of the null hypothesis are

conducted with a significance level of 0.01. The p-values and average effects are summarized in Table 7 for Louvre, Belleville over the summers of 2013 and 2014.

Table 7: p-value and average statistically significant (CI: 0.99) effect at Louvre, Belleville and Louvre using the Belleville control station over the summers of 2013 and 2014

Parameter	Height	Louvre		Belleville		Louvre with Belleville control	
		p-value	Average effect	p-value	Average effect	P-value	Average effect
Air temperature	1.5 m	0.000324	-0.25°C	0.134383	NS	0.001035	-0.24°C
	4 m	0.00131	-0.14°C	0.482932	NS	0.020352	NS
Relative humidity	1.5 m	6.18E-11	+1.46%	0.037265	NS	6.92E-07	+1.87%RH
	4 m	9.26E-09	+0.93%	0.298622	NS	1.45E-07	+1.33%RH
MRT	1.5 m	0.000127	-0.40°C	0.779618	NS	0.000813	-0.70°C
UTCI	1.5 m	0.000346	-0.29°C	0.368533	NS	0.150749	NS

At the Louvre site, the p-value is much lower than 0.01 for all parameters, i.e. the daily effects observed are highly statistically significant. On the other hand, this is not the case at the Belleville site. With a significance level of 0.05, only 1.5-m RH shows a significant daily effect.

This confirms that pavement-watering at Louvre is far more effective than at Belleville where its daily effects cannot be clearly separated from preexisting background noise. One limitation of the analysis of Louvre effects is the absence of the warmest days observed over both summers, i.e. August 1st and 2nd, 2013. In addition, the influence of the watered area on the control area cannot be excluded due to their proximity. These limitations can be overcome by evaluating Louvre effects against the Belleville control station. The far-right column in Table 7 provides the p-value and average daily effects determined in this manner. Figure 9 and Table 8 summarize the effects found with the 10-minute smoothed data.

Table 8: Duration, mean and maximum values of statistically significant effects for Louvre, using the Belleville control station

Parameter	Height	Duration (hours/day)	Mean effect	Maximum effect
Air temperature	1.5 m	6.2	-0.45°C	-0.82°C
	4 m	7.9	-0.35°C	-0.71°C
Relative humidity	1.5 m	18.0	+2.0%RH	+4.6%RH
	4 m	18.2	+1.5%RH	+3.4%RH
MRT	1.5 m	11.1	-0.60°C	-3.73°C
UTCI		1.3	-0.95°C	-1.46°C

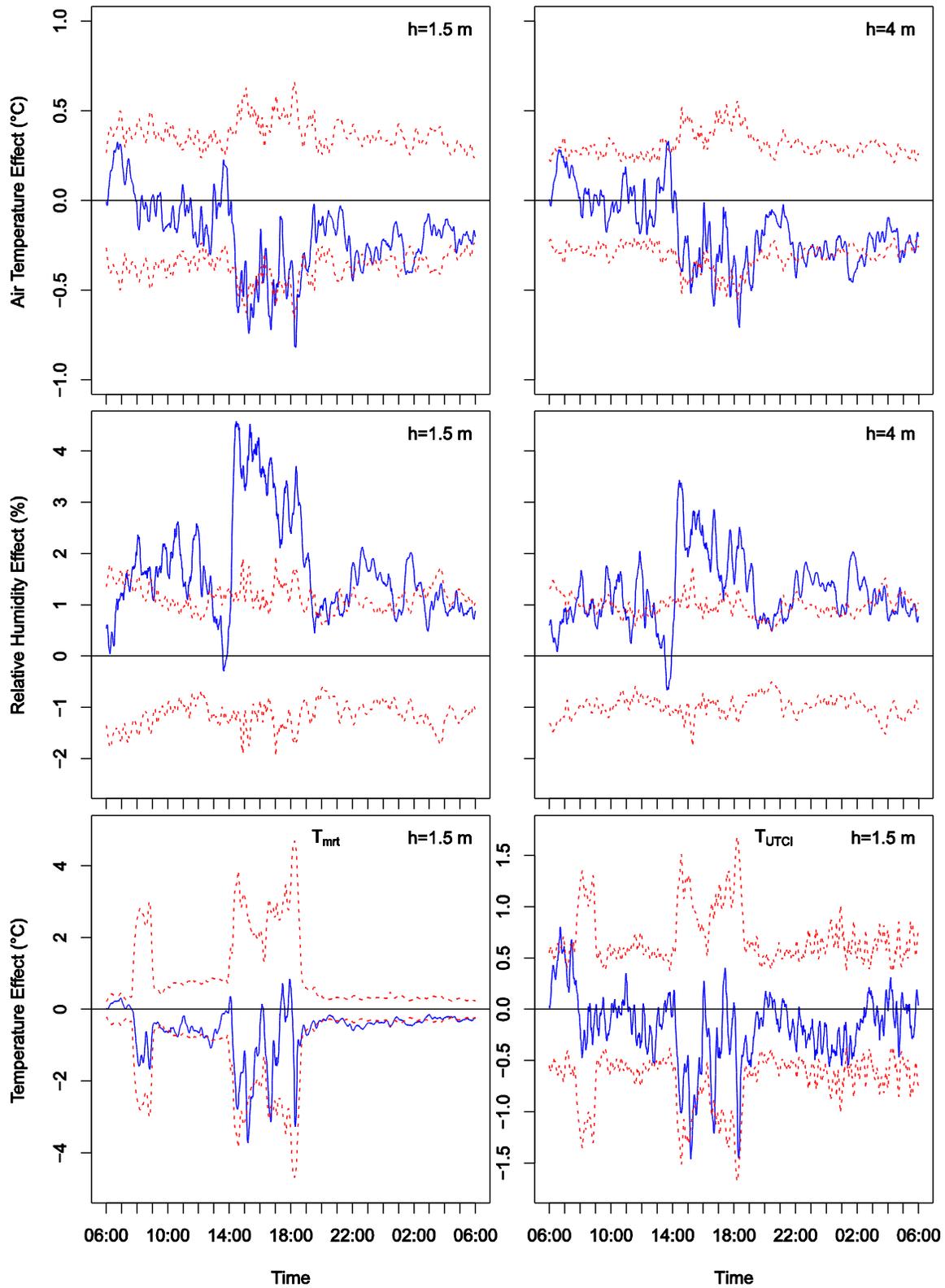


Figure 9: Average watering effect at Louvre detected using the Belleville control stations over the summers of 2013 and 2014 (top to bottom) for T_a and RH at 1.5 m (left) and 4 m (right) height and MRT (bottom left) and UTCI (bottom right). Average effects are solid blue, confidence intervals are dashed red.

Detected maximum effects are increased for all parameters, but only marginally for 1.5-m air temperature and relative humidity. This supports the hypothesis that the watered area influences dry area measurements. However, the statistical significance of the detected effects deteriorates, particularly for air temperature and UTCI. While this can be attributed to increased differences in insolation patterns within this site pair as compared to the initial pairs, this example provides interesting feedback.

While strictly paired stations benefit from reduced data variance and therefore have higher accuracy, strict site selection criteria filter out large numbers of candidates for experimentation. This example demonstrates that the analysis can be successfully conducted in much less favorable conditions if need be. With nearly perpendicular street orientations, paired stations several kilometers apart and very different environments, the method successfully provides comparable values of daily and maximum watering effects. The tradeoff for this added flexibility however is the added signal noise which reduces the statistical significance of the detected effects. In our example, 4-m air temperature and UTCI effects are not statistically significant for this reason.

4. Conclusion

First and foremost, our investigation revealed that the dominant method of directly comparing measurements between experimental and control stations is flawed and cannot reliably detect the real-world micro-climatic effects of UHI countermeasures in cities. The assumption behind this method is that the interstation difference is zero under preexisting conditions. Based on this hypothesis, the interstation difference is directly interpreted as the effect of the implemented UHI countermeasure. However, our continuous measurements over several months at two sites in Paris, France have shown that interstation differences are neither constant nor equal to zero and furthermore exhibit high natural variability. Interstation differences observed after implementation can therefore not be entirely attributed to the studied countermeasure, at least in dense urban environments.

The case study of a pavement-watering experiment was used to demonstrate this as well as develop an alternative methodology. This experiment was conducted over the summers of 2013 and 2014 at two sites in Paris, France, the Louvre site having an approximate N–S street orientation and Belleville with an approximate E-W street orientation. The full width of the Louvre site was watered from 6:30 am to 11:30 am and from 2 pm to 6:30 pm, while only a third of Belleville was watered from 7 am to 7 pm without interruption.

The alternative method consists of a two-sample t-test applied to the difference between mean interstation differences on watered and reference days. The method was successfully tested with data collected at well-paired stations, but also with stations paired between sites, despite their large differences.

Results show that pavement-watering is an effective means of reducing maximum heat stress, while having statistically significant although small effects on nighttime temperatures, thus slightly reducing UHI intensity.

Daily-averaged data was considered and revealed that average watering effects were statistically significant in the case of 100% watering at Louvre, but not so with one-third watering at Belleville. Average effects at Louvre reached -0.25°C and -0.14°C for 1.5- and 4-m air temperature, $+1.5\% \text{RH}$ and $+0.9\% \text{RH}$ for 1.5- and 4-m relative humidity, -0.40°C for MRT and -0.29°C for UTCI equivalent temperature.

The method was also applied to the difference in the mean interstation-difference profiles on watered and reference days. We found that watered days were cooler and more humid than reference days in varying intensity over the course of the day. However, these effects weren't always statistically significant. Relative humidity, followed by MRT, air temperature and UTCI, were most often affected in a statistically significant manner by pavement-watering. Furthermore, significant effects occurred most often at night for air, mean radiant and UTCI-equivalent temperatures, while they occurred most often during the day for relative humidity. However, maximum significant effects occurred during the day, when conditions are hottest and driest. Maximum reductions of 0.79°C and 0.57°C occurred for 1.5- and 4-m air temperature, 1.67°C for MRT and 1.03°C for UTCI-equivalent temperature. Maximum increases of 4.1%RH and 2.8%RH occurred for 1.5- and 4-m relative humidity.

The methodology presented here was applied to pavement-watering which has the advantage over other more permanent UHI countermeasures of being immediately reversible. Indeed, when watering is not taking place, the study sites revert to their preexisting dry state. Firstly, this greatly facilitated the assessment that interstation differences are not equal to zero in the absence of watering. Had measurements begun only after a permanent UHI countermeasure had been put in place, this may have been overlooked entirely. Secondly, it allowed us to record data that could then be used to build an average interstation difference profile for both watered and reference days which could then be compared with the help of our statistical analysis method.

In the case of long-lasting countermeasures, it is not possible to record reference data once the measure has been implemented. It is therefore necessary to start recording sufficiently ahead of countermeasure implementation to allow for enough reference data to be recorded. This data is crucial and must provide a representative image of the preexisting interstation differences. Since weather conditions are random, there is no telling how long this reference period must last and it will depend on the weather conditions of interest. We estimate that it may range from several weeks up to a few years. In our case, heat-wave conditions were the focus point. While we were fortunate that the summer of 2013 exhibited such a large number of relevant days and was sufficient for our analysis, the summer of 2014, with only two watered and five reference days, was not as interesting from this perspective.

The length of the investigation period is one of the limits of the method. Requiring data series spanning over several months implies that the only change expected is the implementation of the UHI countermeasure. However, urban environments are ever changing and thus preexisting conditions determined over a certain period may become rapidly obsolete in certain areas. This adds additional burden to the site selection criteria which must also be relatively stable over the full investigation period. In addition, it was found that site selection criteria can be made more flexible in exchange for a loss in analysis precision by using station pairs whose urban configurations are not as identical as the ones selected here.

Further research is needed to continue to collect data for both reference and watered days and thus continue to strengthen our findings on the effects of pavement-watering. In addition, application of our methodology at other sites with other UHI countermeasures will provide additional feedback as to its relevance and applicability in the field. Unfortunately, since the investigation period must be long, so will the time before significant feedback has been gathered.

5. Acknowledgements

The authors acknowledge the support of Météo-France and APUR (Parisian urban planning agency) as well as the Green Spaces and Environment, Roads and Traffic and the Waste and Water Divisions of the City of Paris during the preparation phase of this experiment.

Funding for this experiment was provided for by the Water and Sanitation Department of the City of Paris.

6. Nomenclature

<i>Symbol</i>	<i>Quantity</i>	<i>[SI unit]</i>
<i>a.g.l.</i>	Above ground level	
BMI_{Max}	Maximum biometeorological index	[°C]
BMI_{Min}	Minimum biometeorological index	[°C]
H/W	Urban canyon aspect ratio	[-]
μ	Average parameter value	
MRT	Mean radiant temperature	[°C]
<i>RH</i>	1.5-m relative humidity	[-]
RH^{4m}	4-m relative humidity	[-]
T_a	1.5-m air temperature	[°C]
T_a^{4m}	4-m air temperature	[°C]
T_g	Globe temperature	[°C]
T_x	Maximum air temperature	[°C]
T_n	Minimum air temperature	[°C]
UHI	Urban heat island	
UTCI	Universal Thermal Climate Index	[°C]
v	Wind speed	[m/s]
WBGTT	Wet-bulb globe temperature	[°C]

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