Measuring the real-world effects of urban heat island countermeasures: a case study of pavement-watering

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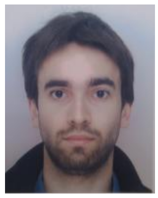
Martin Hendel

Nomenclature

a.g.l.	above ground level
stat. sign.	statistically significant
UHI	urban heat island
WBGT	wet bulb globe temperature

1. Introduction

Typical countermeasures to urban heat islands (UHI) include the use of cool materials or urban greening. Such measures have been studied in the lab or on small-scale demonstrators for decades. Such tests have provided a basis for the simulation of larger scale implementations which provide assistance for decision-makers trying to reduce the impact of UHIs in cities. However, large-scale implementations have only seldom been investigated in the field (Bowler, Buyung-Ali, Knight, & Pullin, 2010; Santamouris, 2013). As a result, few tools have been developed and tested to analyze data from field measurements to evaluate the effects of UHI countermeasures.

In this regard, pavement-watering stands out, with several street-scale field experiments conducted since the 1990's (Bouvier, Brunner, & Aimé, 2013; Kinouchi & Kanda, 1997; Maillard, David, Dechesne, Bailly, & Lesueur, 2014; Takahashi, Asakura, Koike, Himeno, & Fujita, 2010; Yamagata, Nasu, Yoshizawa, Miyamoto, & Minamiyama, 2008). In an attempt to find relevant analysis tools developed for these field studies of pavement-watering, a short review is conducted.

2. Review of field analyses methods

As described, few UHI countermeasures have been studied in the field (Bowler et al., 2010; Santamouris, 2013). Pavement-watering is an exception with several studies conducted since the 1990's in Japan and more recently in Europe (Bouvier et al., 2013; Kinouchi & Kanda, 1997; Maillard et al., 2014; Takahashi et al., 2010; Yamagata et al., 2008). All of these studies are conducted at the street-scale, except for Takahashi et al. (2010) which conducts watering at the district-scale.

Kinouchi and Kanda (1997) and Takahashi et al. (2010) are set in Nagaoka City in Niigata Prefecture on the West coast of Japan, while Yamagata et al. (2008) describe watering in Tokyo. Finally, Bouvier et al. (2013) and Maillard et al. (2014) respectively conduct watering in Paris and Lyons, France, presented as a potential countermeasure for heat waves.

All studies conduct watering on standard impervious pavement surfaces except for Yamagata et al. (2008) which sprinkle water-retaining pavements. Where solar irradiance data is provided or can be derived, it is apparent that solar masks are low, except for Yamagata et al. (2008) and Maillard et al. (2014).

Fig. 1 provides maps of case (watered) and control station positions for each article where provided. In all of the considered field trials at the street scale, the analysis method used to determine micro-climatic effects is a direct comparison between case and control station measurements. Indeed, Kinouchi and Kanda (1997), Yamagata et al. (2008), Bouvier et al. (2013) and Maillard et al. (2014) each base their analyses on measurements made at a watered street and at an unwatered street.

Kinouchi and Kanda (1997) compare measurements at site A with identical ones at site B. Yamagata et al. (2008) consider five areas, but only provide measurement comparisons between blocks 1 and 4. Bouvier et al. (2013) do not provide a map of their watered and control station positions, however they inform the reader that the control station is positioned on the same street. Finally, Maillard et al. (2014) compare results from stations 13 and 16.

Takahashi et al. (2010), which conduct watering at the district scale, consider two watered areas and two control areas. For both watered areas, control areas are defined in the immediate surroundings. As can be seen in Fig. 1, each watered area is equipped with four manual thermo-hygrometers, while each control area is equipped with five automatic thermo-hygrometers. The watered and control area averages are compared to determine the impacts of pavement-watering.

In all of these cases, the observed difference between watered and unwatered measurements is interpreted as the effect of pavement-watering. The resulting effects of pavement-watering on air temperature and humidity are reported in Table 1.

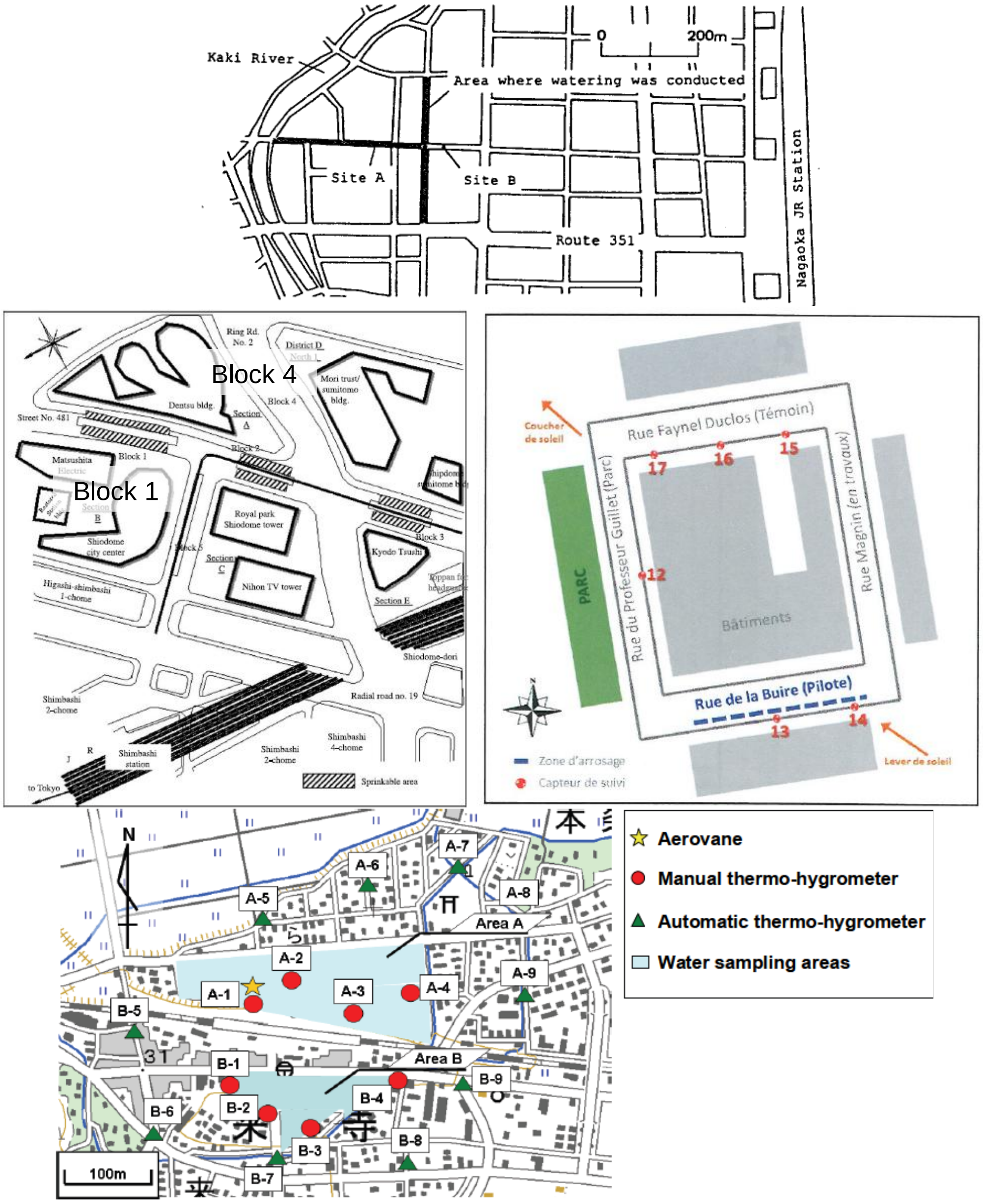

Fig. 1 Watered and control station positions. Top: (Kinouchi & Kanda, 1997); left: (Yamagata et al., 2008); right: (Maillard et al., 2014); bottom: (Takahashi et al., 2010)*.*

Table 1: Reported maximum impacts of pavement-watering

Authors	Height	Air temperature	Air humidity	Globe temperature	WBGT
(Kinouchi & Kanda, 1997)	1.5 m	-1°C	+4%	-4°C	-
(Yamagata et al., 2008)	0.5 m	-2.5°C	-	-	-2°C
(Takahashi et al., 2010)	0.9 m	-4°C	-	-	-
(Bouvier et al., 2013)	2 m	-0.4°C	+4%	-	-
(Maillard et al., 2014)	1.5 m	-	-	-	-0.5°C

Kinouchi and Kanda (1997) describe the difference in measurements made at sites A and B one hour before and one hour after pavement-watering. According to them, these are “either averaged 0, or the temperature was much higher and the humidity lower at Site A.” They conclude from this “that temperature and humidity […] were affected greatly by the watering.” No other authors describe their measurements in the absence of watering.

It is unclear how valid Kinouchi and Kanda’s statement is as it is based on observations conducted over a total of two hours. Indeed, differences between sites may vary over the course of the day and observations made at one time during the day are not necessarily valid at others. Generally-speaking, different sites are likely to have different behavior unless they are perfectly identical and it is unlikely that this can be captured with measurements conducted over a few hours.

To verify this, we use a pavement-watering experiment conducted in Paris, France over the summers of 2013 and 2014. Continuous measurements conducted at watered and control areas will demonstrate that the direct comparison method is ill suited to the purpose of quantifying the micro-climatic effects of pavement-watering and other UHI countermeasures. An alternative method will be proposed based on the evaluation of preexisting differences between paired case-control sites.

2. Materials and Methods

The pavement-watering experiment conducted in Paris over the summers of 2013 and 2014 will be briefly described. Further details may be found in (Hendel, Colombert, Diab, & Royon, 2014, 2015).

The field experiment was conducted at two sites in Paris, France between July and September 2013 and 2014: Louvre and Belleville. Case and control stations were located on rue du Louvre in the 1st and 2nd Arrondissements and rues Lesage and Ramponeau, respectively. Site locations within Paris are illustrated in Fig. 2, while relative positions are illustrated in

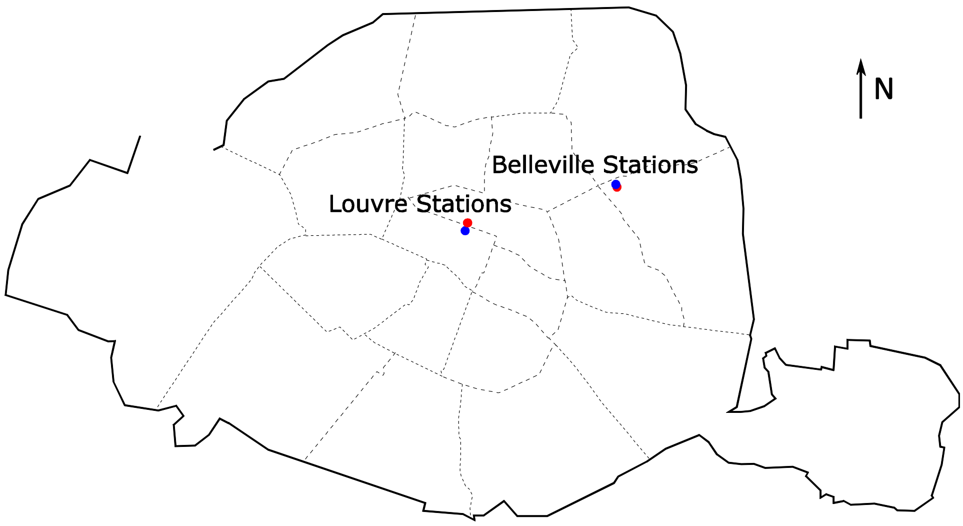

Fig. 2 Experimental station positions in Paris. Watered stations are in blue, control stations in red.

Watering was conducted if certain weather conditions were met, similar to heat wave conditions for Paris but less strict. In short, three-day averaged minimum and maximum temperatures had to exceed 16° and 25°C, while wind speed was lower than 10 km/h and the sky was clear. In Paris, heat wave conditions are met if air minimum and maximum air temperatures exceed 21° and 31°C for three consecutive days. Considering these conditions, watered days are of Pasquill Stability Class A or A-B (Pasquill, 1961). For better comparability, all considered unwatered days, referred to as reference days, will also be of Pasquill Stability Class A or A-B.

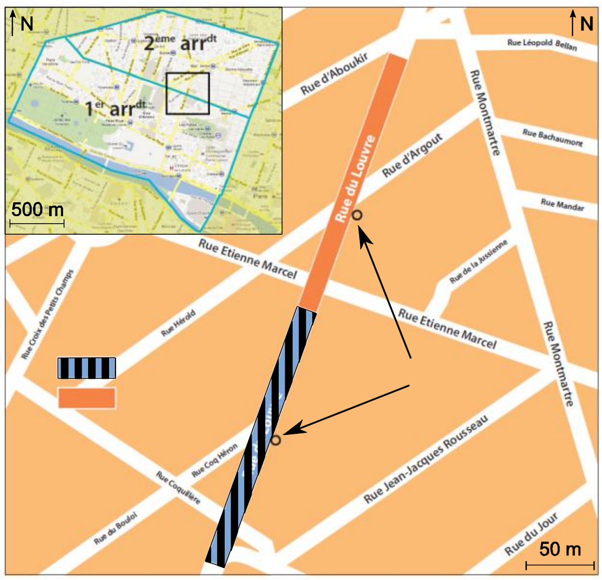

Fig. 3 Case and control station positions for the Louvre site.

Paired stations were identically equipped with sheltered air temperature and humidity sensors 1.5 m and 4 m above ground level (a.g.l.), a black globe thermometer 1.5 m a.g.l. and a wind sensor 4 m a.g.l.. Table 2 summarizes the instruments used, their make and model as well their height and uncertainty, while illustrates weather station design.

Table 2: Instrument type, measurement height above ground level and accuracy

Parameter	Instrument	Model	Manufacturer	Height	Symbol	Uncertainty
Air temperature	Sheltered Pt100	DMA 672.1	LSI LASTEM	1.5 m and 4 m	T_a	0.10°C

As watering begins between 6:15 am and 7 am local time (UTC +2), data is presented over 24 hours beginning at 6 am and ending at 5:59 am the following day, e.g. July 8th refers to data collected from July 8th at 6 am until July 9th at 5:59 am. Over the course of both summers, a total of 12 watered days were observed as well as 28 reference days.

3. Results and Discussion

We begin by investigating the validity of the hypothesis that station measurements are equal in the absence of watering.

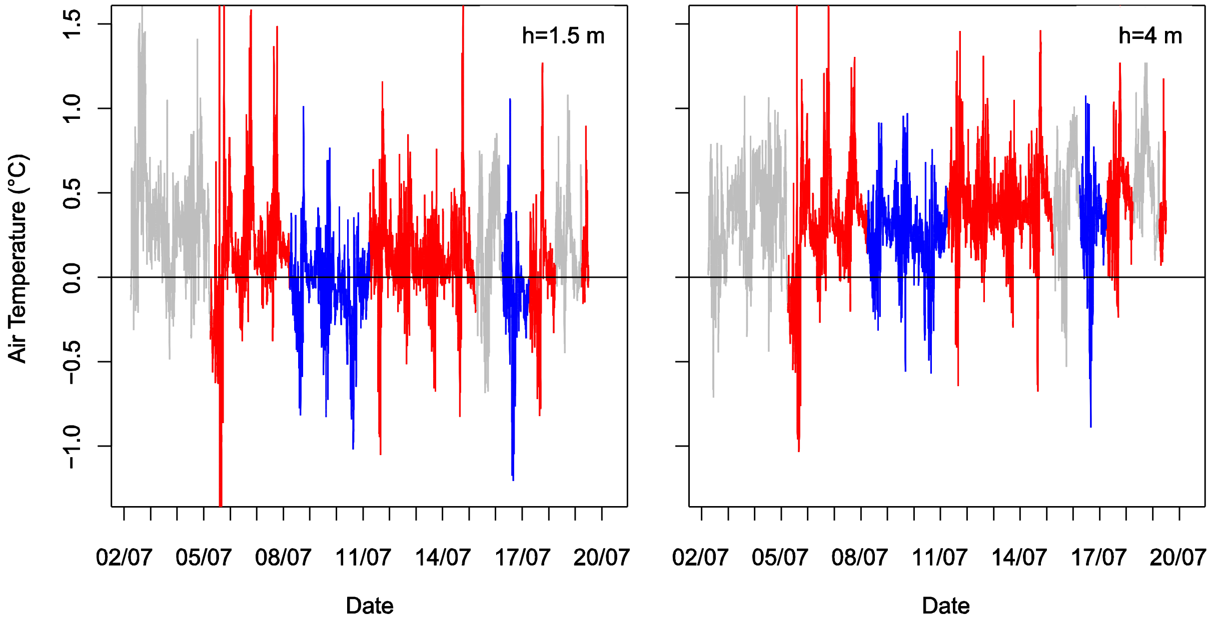

Fig. 4 Air temperature difference between case and control stations from July 2nd to July 20th, 2013 at Louvre site. Red: reference days; blue: watered days; grey: incomparable days.

3.1 Direct comparison between stations

Firstly, the 5-minute smoothed difference between case and control stations for air temperature 1.5 m and 4 m a.g.l. is presented for the Louvre site in Fig. 4 from July 2nd to July 20th, 2013. Days in red and blue are of Pasquill Class A or A-B, respectively without and with watering.

As can clearly be seen, the difference between stations is not equal to zero on days without watering. In fact, the difference is not constant and changes over the course of each day, and also from one day to the next.

This clearly demonstrates that differences between stations cannot be ignored when attempting to quantify the effects of UHI countermeasures in the field. We therefore propose an alternative method which will take these into account.

3.2 Alternative method

Description

We therefore propose an alternative analysis method, consisting of a two-sample t-test of the difference of the interstation profile on watered days compared to reference days. First, the average interstation profile is established for reference and watered days. All reference and watered day observations are grouped by time of day by the minute. For example, each observation of the interstation difference 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 reference days and as many for watered days. A sample mean and variance can then be calculated for each minute. The series of the minute-by-minute sample means is the sample average interstation difference profile for reference or watered days.

Comparing the obtained mean interstation profiles will only provide a partial answer to the effectiveness of pavement-watering. Indeed, given the statistical nature of meteorological observations, the difference between means on watered and reference days must be tested for statistical significance. This is conducted in the following manner.

To test the difference between the mean value at the i-th minute on watered (μ_i^{wet}) and reference days (μ_i^{dry}), a two-sample t-test with a significance level of 0.05 is conducted. 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. Both hypotheses can be summarized as follows, for $i \in [\![1;1440]\!]$:

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

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

If the p-value obtained from the test is lower than the significance level of 0.05, the null hypothesis is rejected, i.e. the watered day mean is lower than the reference day mean for the considered parameter.

The method is now applied to the field measurements from our pavement-watering experiment.

Application to air temperature measurements

Fig. 5 illustrates the average effect of pavement-watering on air temperature 1.5 m and 4 m a.g.l.

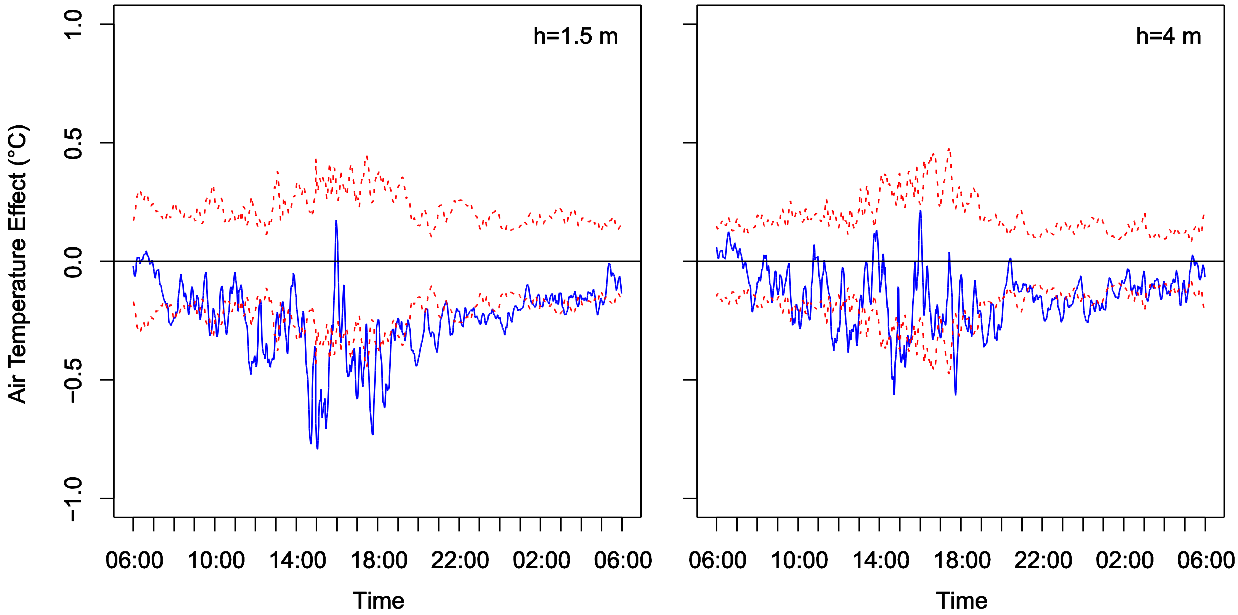

Fig. 5 Average watering effect at Louvre for air temperature. Average effects are solid blue, confidence intervals are dashed red.

The solid blue curve is the difference between mean interstation difference profiles on watered and reference days, while the red dashed curve represents the confidence interval. The effect of watering is only statistically significant (stat. sign.) if the blue curve is outside of the confidence interval.

As can be seen, pavement-watering has stat. sign. effects. Maximum temperature reductions of 0.79°C 1.5 m a.g.l. and 0.57°C 4 m a.g.l. are reached at approximately 6 pm, when weather conditions are hottest (not shown). However, effects are not always stat. sign. Indeed, effects before 7:30 am are not stat. sign. and only marginally so after 2 am.

While the confidence interval is in the order of +/- 0.2°C before 1 pm and after 7 pm, it increases to 0.4°C between 1 and 7 pm, i.e. during insolation. This sensitivity to insolation is caused by the use of naturally-ventilated instrument shields rather than actively-ventilated ones. Indeed, measurements at paired stations would be less sensitive to sudden changes in insolation in the latter case.

3.3 Generalization and application to the study of other UHI countermeasures in the field

Our analysis method was successfully used to differentiate between naturally occurring interstation differences and those caused by pavement-watering.

Firstly, the process described is not specific to the analysis of high frequency measurements as conducted here. Indeed, it can be applied to determine the daily effects of pavement-watering if the series of daily-averaged interstation differences is considered instead of minute-by-minute data.

Furthermore, the method applied is not limited to the study of pavement-watering, but can be generalized to other UHI countermeasures. Certain precautions are required however as pavement-watering is not a permanent countermeasure and can be turned on or off at will. Indeed, once watering has stopped, the test sites revert to their preexisting state in a few hours after drying. This allowed us to conduct our reference and watered day measurements simultaneously.

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 monitoring test sites sufficiently ahead of time 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 a large number of relevant days and allowed us to conduct our analysis, the summer of 2014, with only two watered and five reference days, would not have provided sufficient data to conduct a reliable analysis.

The length of the investigation period is one of the limits of the proposed method. Requiring data series spanning over several months or years implies that the only change expected is the implementation of the UHI countermeasure. However, urban environments are ever changing and 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.

4. Conclusions

Our analysis has demonstrated that the commonly-seen direct comparison of case and control measurements to determine the effects of pavement-watering and other UHI countermeasures is ill-suited to the task. Indeed, sites are never perfectly paired and differences are cannot be considered constant, especially in dense urban environments.

An alternative statistical analysis method was developed and successfully used to determine the effects of pavement-watering in an experiment conducted in Paris, France over the summers of 2013 and 2014. Proposals to generalize its application to other UHI countermeasures were made.

The strength of our findings on the effects of pavement-watering will increase as data collection continues. Paths for improvement include the use of high precision instruments calibrated against each other on a regular basis in a laboratory-controlled chamber and the use of aspirated solar shelters to eliminate the influence of insolation on air temperature and humidity measurements. Furthermore, the influence of the measurement cage on weather instruments must be better quantified.

Applications of our methodology to other sites and 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 can be gathered.

Acknowledgment

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