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Measuring the effects of urban heat island mitigation techniques in the field: 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 their micro-climatic effects are scarce, yet are essential to properly evaluate their effectiveness and that of anti-UHI policies. The standard approach to determining their micro-climatic effects is to study the difference in measurements made at case and control stations. However, measurements conducted during a pavement-watering experiment in Paris, France reveal that this method mistakes preexisting differences for pavement-watering effects. An alternative approach based on a two-sample *t*-test was therefore developed and tested with the pavement-watering field trial as a case study. The proposed method proved able to determine the effects of pavement-watering, without misinterpreting preexisting differences. In the process of the case study, watering was found to reduce maximum daily heat stress, while having smaller statistically significant UHI-reducing effects. The greatest effects were reached during the day for all parameters with maximum 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, while UHI-mitigation reached up to −0.22 °C. The methodology developed is not specific to pavement-watering and recommendations for its improvement and its application to the field-evaluation of other UHI countermeasures are made.

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 (California Energy Commission, 2010). Such policies are supported by the growing scientific literature on the topic of UHI countermeasures, yet proper evaluation tools are required in order to analyze their effectiveness in the field.

To date, 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 (Li et al., 2013; Karlessi et al., 2011; Kubo et al., 2006; Levinson et al.,

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Nomenclature

Symbol	quantity (SI unit)
a.g.l.	above ground level
BMI_{Max}	maximum biometeorological index (°C)
BMI_{Min}	minimum biometeorological index (°C)
c	water specific heat (J/kg K)
E	evaporation rate (g/s)
G	pavement heat flux density (W/m^2)
H/W	urban canyon aspect ratio (–)
H	sensible heat flux density (W/m^2)
l	latent heat of vaporization (J/kg)
L_{down}	downwards longwave radiation (W/m^2)
L_{up}	upwards longwave radiation (W/m^2)
μ	average parameter value
MRT	mean radiant temperature (°C)
Φ	pavement-watering cooling flux density (W/m^2)
ρ	water density (kg/m^3)
RH	1.5-m relative humidity (–)
RH^{4m}	4-m relative humidity (–)
R_n	net downwards radiation (W/m^2)
S	downwards shortwave radiation (W/m^2)
S_{ref}	upwards reflected shortwave radiation (W/m^2)
stat. sign.	statistically significant (–)
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)
T_S	pavement surface temperature (°C)
T_W	sprinkled water temperature (°C)
t_0	water cycle period (s)
UHI	urban heat island
UTCI	Universal Thermal Climate Index (°C)
v	wind speed (m/s)
V_S	sprinkled water volume (L/m^2)
WBGT	wet-bulb globe temperature (°C)

2007; Takebayashi and Moriyama, 2007, 2009). Results indicate that surface temperatures are significantly reduced compared to standard materials. This in turn is expected to result in lower contributions to urban heating. Equivalent work on green spaces has mostly focused on existing parks (Jauregui, 1990; Ca et al., 1998). Findings indicate cooling of up to a few degrees through the combined effects of evapotranspiration and shading. However, field evaluations and monitoring of large-scale uses of cool materials or new urban green spaces remain scarce (Santamouris, 2013; Bowler et al., 2010), with most large-scale micro-climatic effects being studied with the help of computer simulations (Akbari et al., 2001; Nakayama et al., 2012; Météo France and CSTB, 2012).

Pavement-watering stands out as an exception and has been studied in the field via several independent studies. These may be useful in providing appropriate field analysis methods for other UHI countermeasures. Japan began work in the 1990's with the use of preexisting pavement-watering installations in Nagaoka City or block-scale demonstrators in Tokyo (Kinouchi and Kanda, 1997; Kinouchi et al., 1998; Takahashi et al., 2010; Yamagata et al., 2008). More recently, the city services of Paris or Lyons in France have conducted field studies with the use of cleaning trucks or permanent watering infrastructure prototypes (Bouvier et al., 2013; Maillard et al., 2014). In all of these cases, the analysis is based on a direct comparison between case and control measurements, the observed interstation difference being interpreted as the effect of pavement-watering.

Unfortunately, this analysis method is flawed. Indeed, it tacitly assumes that measurements at two different stations are equal in normal conditions, i.e. prior to UHI countermeasure implementation. Given the inherent complexity of urban environments, this is highly unlikely. Since direct case-control station comparisons do not account for preexisting differences between measurement stations, the method may misinterpret them as the studied countermeasure's effect.

This paper proposes an alternative statistical analysis method based on a two-sample *t*-test of differences. A pavement-watering experiment will be used as a test application of the method. This experiment was conducted in Paris, France during