SPATIAL VARIATION OF THE CANOPY-LEVEL URBAN HEAT ISLAND IN SINGAPORE

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1. INTRODUCTION

The urban heat island (UHI), i.e. elevated nocturnal air temperatures in built-up areas compared to undeveloped natural surroundings, is a well-know climatological phenomenon associated with cities. Its negative effects in hot and humid climates include decrease in human comfort and productivity and increase in energy usage associated with the need for air conditioning. It is therefore important to ensure that the rapidly expanding cities of the developing world which are often located in (sub)tropical climate zones, incorporate climatological concerns and UHI mitigation measures in their design to provide a better living and working environment for a large segment of the world's inhabitants and reduce the carbon emissions associated with significant cooling needs. Although the UHI has been thoroughly researched in cities located in temperate or hot/dry climate regions, there is a need to establish long-term measurement programs to monitor the exact nature of (sub)tropical urban climates (Roth, 2007).

Singapore (1 °N, 104 °E) is an island state with an area of ~700 km^2 located at the southern tip of the Malaysian peninsula. Its geographical location translates to an equatorial wet climate with consistently high monthly mean temperatures (yearly average of ~27 °C), rainfall (yearly total of ~2300 mm) and exposure to the Asian monsoon with surface winds predominantly from the northeast (southwest) during the winter (summer) months. Since gaining independence from Malaysia in 1965, Singapore has undergone rapid urbanization. Population increased from 1.8 million in 1965 to 4.7 million in 2008. Land-use change has also been rapid, with a doubling of the built-up area between 1965 – 2000 and a corresponding decrease in forest and farm areas. Much of this urban development is manifested by numerous high-rise residential apartments developed by the Housing Development Board (HDB) that house the vast majority (~80%) of the local population.

The objectives of the present study are to systematically study the spatial variation of the near-surface (canopy-layer) UHI in Singapore, derive statistical relationships of the UHI with land-use and urban geometry and derive empirical relationships to produce an UHI map covering the entire Singapore region. The subsequent sections introduce the methodology and preliminary results.

2. METHODOLOGY

To be able to derive statistical relationships between the UHI and the various parameters affecting urban temperatures, measurment locations were selcted which represent a wide variety of urban land-uses representative of Singapore. They include a central business district (CBD), commercial areas, HDB high-rise apartments, low-rise terrace housing, low-rise detached residential, low-rise industrial, agricultural, open areas with short vegetation, dense tropical forest, urban parks and coastal areas (Figure 1). The current sensor network consists of about 35 locations spread across the city (Figure 2), however, this number is somewhat variably owing to the disappearance of sensors and addition of new ones. Care was taken to ensure that the area surrounding a particular measurement location is representative of a specific land-use within a 500 m circle centered on the site (Figure 3). Given the fragmented nature of the Singapore urban landscape this requirement imposed severe limitations on the choice of potential sites but is important to ensure meaningful measurements.

Temerature and relative humity are recorded with ONSET HOBO^{TM} H8 Pro and ONSET HOBO^{TM} Pro V2 sensors housed inside HOBO^{TM} radition shields. This sensor offers high accuracy, internal memory and low power consumption. Practical considrations guided the choice for using, in most cases, lampposts to mount the sensor at about 2 m above ground level. Measurements started in February 2008 and are continuing, sampling temperature and relative humidity at 10 minute intervals. All sensors were compared against each other at the beginning of the study and the data showed excellent relative agreement between sensors (< +/-0.1ºC for temperature and < +/-2% for relative humidity). The same result was found in a similar comparison exercise using 40 HOBO sensors (see Balázs *et al.*, 2009). Potential effects of the lamppost on the readings were also investigated by measuring the difference in temperature readings between a sensor mounted at the usual 10 cm distance from the lamppost and another sensor located 40 cm from the lamppost. Although the sensor close to the lamppost systematically measured slightly higher temperatures, the differences are small, and in particular at night (which is the focus of the present research) the bias is less than 0.05 ºC (Figure 4) which is below the accuracy of the sensor (0.2 ºC).

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Figure 1: Examples of typical land-uses in Singapore. Clockwise from top left: CBD, commercial, HDB high-rise apartments, low-rise detached residential, open with short vegetation, undeveloped natural area.

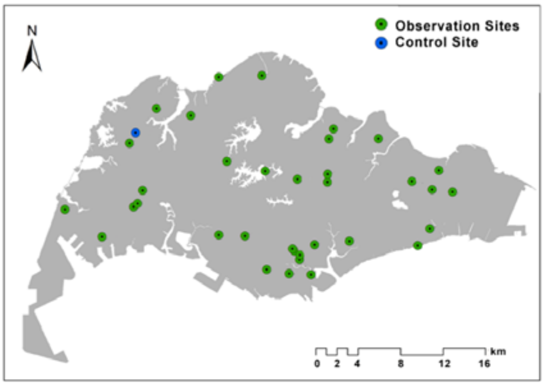

Figure 2: Geographic distribution of HOBO™ sensors across Singapore island.

Figure 3: Sensor location in industrial area. Yellow (green) shades are circles of 100 (500) m radius centered on the site.

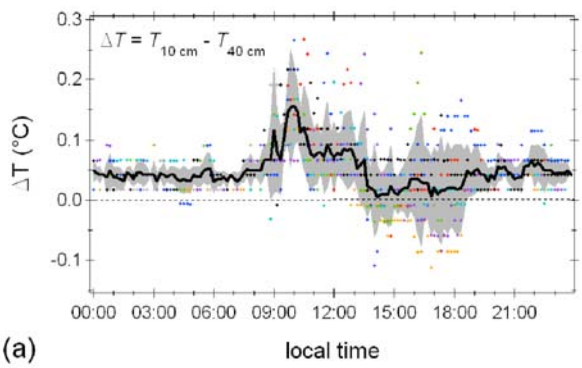

Figure 4: Mean (7 days) diurnal variation in March 2009 of the difference in temperature measured by a HOBO™ mounted 10 and 40 cm away from the actual lamppost, respectively (Velasco 2009, pers. Comm.).

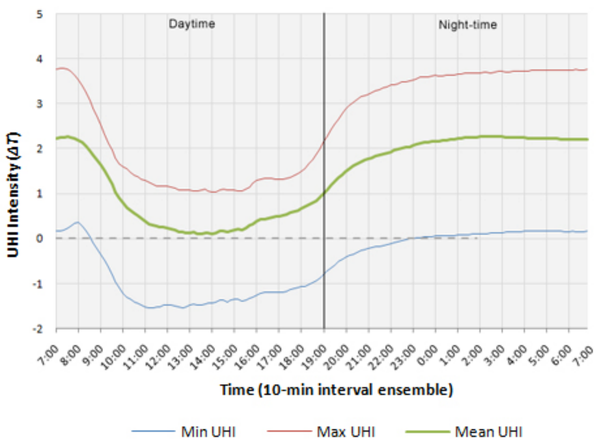

Figure 5: Mean ensemble UHI for all stations in Fig. 2 and all weather conditions for the period February 2008-2009 (green line). The mean for the station with the maximum (minimum) UHI is given by the red (blue) line, respectively.

3. PRELIMINARY RESULTS

For this preliminary analysis the station chosen to represent the undeveloped, rural background was located in the northwest of the island ("Control Site" in Fig. 2) which is characterized by secondary rain forest, military training grounds and agricultural farms. The immediate surrounds of the station is a mix of open grassy area and secondary rainforest. Since several sites which could be classified as "rural" are available, subsequent analysis will provide an assessment of the influence the definition of "rural" can have on the determination of the UHI. The diural variation of the average UHI (temperature difference between any of the urban locations and the "Control Site") for all weather conditions for a period of 13 months between February 2008-2009 shows a mean nocturnal warming of about 2 ºC across the entire city (Fig. 5). This is the average of all land-use types sampled with a bias towards urban/suburban surface covers. The largest average UHI itensities of ~3.8 ºC were measured at the commercial site in the vicinity of Orchard Road which is the main shopping and entertainment district of Singapore (red line in Fig. 5). The same site also experienced the highest UHI magnitude in a past study (Chow and Roth 2006). The highest individual-day UHI magnitude measured during the present observation period was 7.8 ºC on 2 May 2008 at 22:30 hrs. The lowest values (blue line in Fig. 5) are associate with readings taken inside a primary rain forest in the center of Singapore island. During daytime the temperature difference is negative which can be expected given the shaded location.

In order to attribute UHI values to site-specific characteristics, metadata was recorded including heigh-to-width ratio (H/W), sky-viw-factor (SVF), percent greenspace, percentage paved, length of road network (all within an area of 100 and 500 m radius, respectively centered on the site) and distance to nearest water body. Based on regression analysis using data from all weather conditions, percentage vegetation cover within a 100 m radius showed the strongest predictive capability, followed by percentage built-up area (Fig. 6). Corresponding correlation coefficients were less when using statistics within a 500 m radius (not shown).

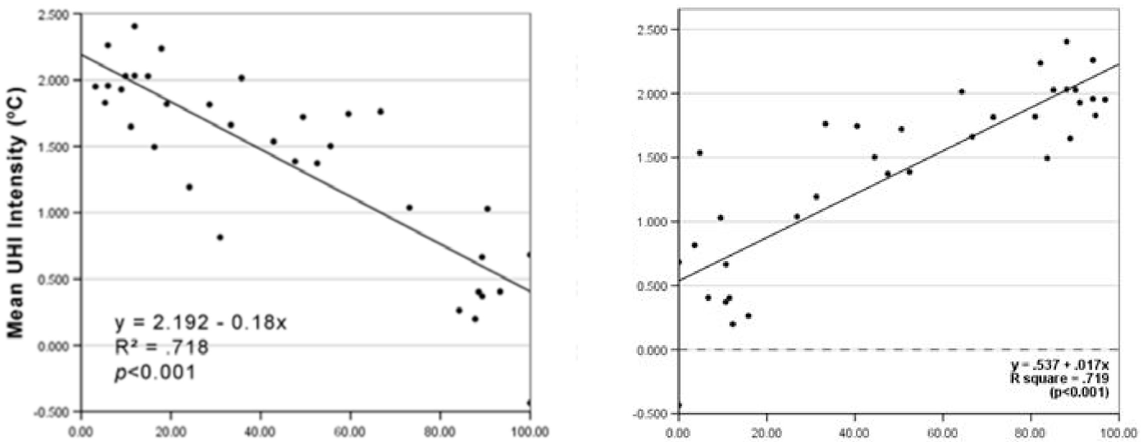

Figure 6: Mean UHI intensity regressed against percentage vegetation (left) and built-up area (right) within a 100 m radius centerd on a particular location.

A stepwise multiple regression model was subsequently run and a two-variable model developed (using percentage vegetation and H/W ratio as the best predictors which were significant for a given confidence level) to predict the mean UHI intensity for entire Singapore based on an island-wide land-use classification with a 500x500 m resolution. Using data from May 2008 (the month when the largest UHI intensities are observed), an UHI intensity map was produced for 02:50 hrs by applying the regression model to each grid cell (Fig. 7). This example shows that most areas in Singapore experience UHI values in exceess of 3 ºC. The coolest loactions are as expected associated with the forest areas in the central catchment reserve, the less devleoped areas in the northwest and a smaller patch in the east where an arfield and heavily vegetated military grounds are located.

Future work will include a more detailed investigation (i) using data from calm and clear conditions only when maximum heat island development can be expected, (ii) of temperature differences across the various "rural" sites and the influence on the UHI intensity, (iii) of the seasonal variability of the UHI and (iv) of particular case studies to determine the influence of local rainfalls on the UHI.

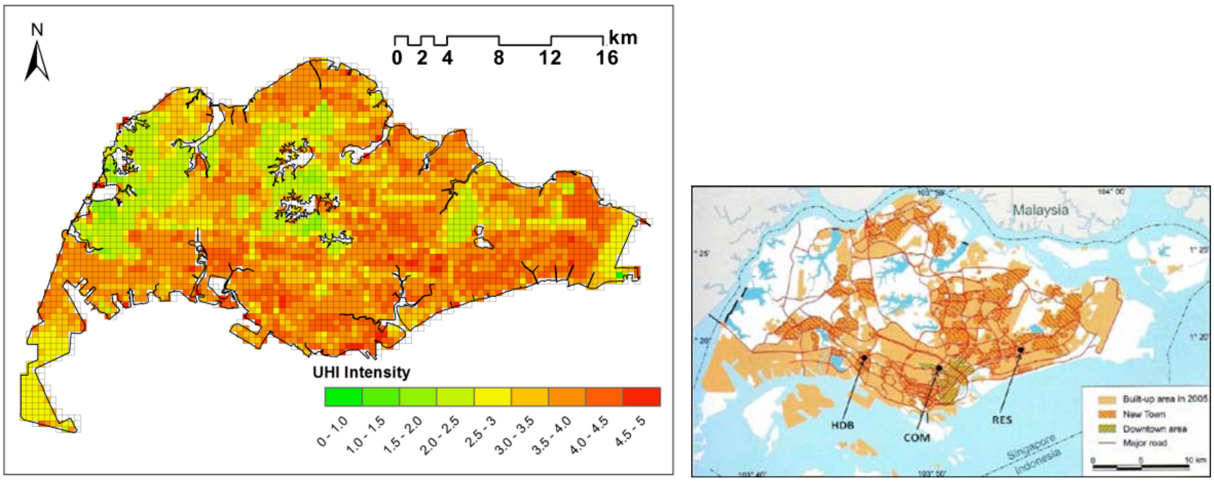

Figure 7: Interpolated UHI intensity map for Singapore for 02:50 hrs in May 2008 based on a multiple regression model (left) and land-use map for 2005 (right; de Koninck *et al*, 2008).

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