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Temporal Statistical Analysis of Urban Heat Islands at the Microclimate Level

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Abstract

Urban Heat Islands (UHI) represent the air temperature difference between urban and rural areas. This study deployed a network of miniature sensors to capture road-side microclimate data in both summer and winter. Temporal variations indicated UHI were evident for all time scales, with daily highest and lowest UHI at around midnight and noon/early afternoon respectively. Meteorological and environmental factors influencing UHI were also statistically analyzed by automatic linear regression models. Regression results suggested solar radiation and greenery density were the most important factors with a negative association with UHI intensities in both seasons.

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Keywords: Microclimate variation; Urban heat islands; Automatic linear regression

1. Introduction

Urbanization is known to disrupt the surface energy balance of a city to a state that is entirely different from that of an ordinary and natural situation. These modifications to the energy balance of a city bring higher temperatures and undesirable thermal impacts to the local urban environment. This impact on local climate in an urban city, in particular with reference to the increase in outdoor temperature, is broadly known as the Urban Heat Island (UHI) effect. Oke [1] and numerous UHI studies have put forth that meteorological conditions and environmental settings play an important role in ameliorating or amplifying UHI. These factors include wind speed, air temperature, solar

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radiation, sky view factor, and greenery density. Although UHI factors and empirical theories have long been established and confirmed, their magnitude and causative importance have remained uncertain [2]. Most research and case studies have been carried out in western countries at the macro scale (regional or city level). There is a clear shortage of micro scale UHI studies at the neighborhood, block or street levels in Asian cities. Besides, UHI research has relied mostly on meteorological data from official weather stations situated in remote areas away from urbanized locations. This constraint has resulted in road-side temperature and UHI measurements being underestimated.

This paper presents a low-cost methodology that deployed small and inexpensive sensors to undertake continuous measurements of microclimate data at two representative urban communities in Hong Kong. The network of sensors recorded road-side temperature and relative humidity at 15-minute interval for 2 weeks in the summer and repeated again in the winter. UHI values were computed and regressed against local meteorological and environmental factors to assess the microclimate effects. The micro-scale examination of UHI can inform better urban planning to improve thermal comfort in a hot and humid subtropical setting.

2. Data and Method

2.1. Study Area

Hong Kong (22º15'N, 114º10'E) is located along the coast of southeast China near the entrance of the Pearl River Delta. The morphology of Hong Kong is a combination of mountainous terrain packed with densely built high-rise buildings. It is also one of the densely populated cities in the world with a high proportion of its population residing in urbanized areas. Hong Kong has a monsoon-influenced humid subtropical climate (Köppen classification Cwa) characterized by hot humid summers and mild winters [3]. Most summer days have high humidity with warm air coming from the southwest, creating local thermal discomfort.

Mongkok (MK) and Causeway Bay (CWB) are urban areas located respectively within the center of the Kowloon Peninsula and northern part of the Hong Kong Island. Both areas are popular residential districts also known to have high levels of commercial and retail activities. These conditions typify microclimate of an urban area affected by UHI.

2.2. Microclimate and Environmental Data

The street-level microclimate data were collected by a network of self-contained temperature and humidity sensors equipped with data loggers. All sensors were calibrated and tested [4], utilizing ice and warm water baths to within ± 1 ºC accuracy. 58 sensors (configured to measure air temperature at 15-minute intervals) were each housed within a non-aspirated solar radiation shield. They were mounted on road-side street sign posts at 2.3m above ground throughout MK and CWB for 17 consecutive days in summer (15 Sept – 1 Oct 2012) and again in winter (18 Jan – 3 Feb 2013). Local meteorological parameters at MK and CWB were also measured at 15-minute intervals using a portable weather station over the same period for 24 hours. Official meteorological conditions for the duration of study were obtained from the Hong Kong Observatory (HKO) to validate the sensors and to explore microclimate variations by comparing the official urban (HKO Headquarter – HKO) and rural (Tsak Yue Wu – TYW) monitoring stations with the sampled sensor readings. A total of seven local meteorological factors were assembled: wind speed, peak wind speed, rainfall, solar radiation, air temperature, relative humidity and wind direction.

Environmental factors at MK and CWB were spatially determined by a 100m circular buffer around each of the sensor measurement locations. Nine environmental factors were derived from digital and census data using a geographic information system: Annual Average Daily Traffic, building volume density, greenery density, road density, topography, sky view factor, social deprivation index, population density and household density.

2.3. Method of Analysis

UHI intensity known as $\Delta T_{(Urban-Rural)}$ measures the difference between air temperature of an urban area and that of the surrounding rural area [5]. The street-level air temperature readings were first compared against the official rural readings to obtain UHI at various locations: UHI_{MK}, UHI_{CWB} and $UHI_{OFFICIAL.}$ Line graphs were plotted to exhibit temporal patterns of UHI over 17 days each for summer and winter.

All seven meteorological and nine environmental variables were correlated with UHI_{MK} and UHI_{CWB}. These factors or predictors would be entered or removed from the regression model depending on the statistical significance of p-values set at 0.05 [6,7]. Four different selection criteria (AICC = Akaike's information corrected criterion; F-Statistics; Adjusted R-squared; and ASE = Average squared error) were used to evaluate the rankings of meteorological and environmental variables for two different seasons in MK and CWB.

3. Results and Discussion

3.1. Accuracy Discussion

The sampled and official readings displayed similar fluctuation cycles over the entire period. Sensor readings were consistently higher (0.26 ºC higher on average and a root mean square error of 0.31 ºC) than the HKO measurements. The Pearson's correlation coefficient (r=1.0) signaled a strong relationship between sensor readings and HKO measurements. In addition, student's t-test exhibited no significant temperature difference (p=0.11) between sensor and official measurements at hourly intervals. All road-side measurements at MK and CWB were also validated against local control and official measurements. The validation outcome indicated that road-side and control measurements were strongly correlated (r>0.81) and their average difference was well within the manufacturer claimed ± 1 ºC measurement accuracy. This study has confirmed that the small sensor is a reliable and accurate device to undertake temperature measurements for UHI research in a location of subtropical climate.

3.2. Temporal Analyses of UHI

Figure 1 depicts the average UHI_{MK} (red line) and UHI_{CWB} (blue line) against $UHI_{Official}$ (grey dotted line) for 17 consecutive days in the summer and winter. In general, the UHI line graphs display similar fluctuation patterns for all locations (MK, CWB, and official), with higher values in the night than at day. UHI_{MK} and UHI_{CWB} were consistently higher than $UHI_{Official}$, with UHI_{MK} at the top most of the time. The highest UHI intensities for the summer and winter periods were 10.4 ºC and 9.5 ºC respectively. In addition, a bimodal peak was observed in some nights for both summer and winter (e.g., 30 Sep to 1 Oct and 18-19 Jan). Also of interest was the summer days with lower UHI intensities coincided with days of heavy rainfall (20-22 Sep) and severe rainstorm (24-25 Sep) [8].

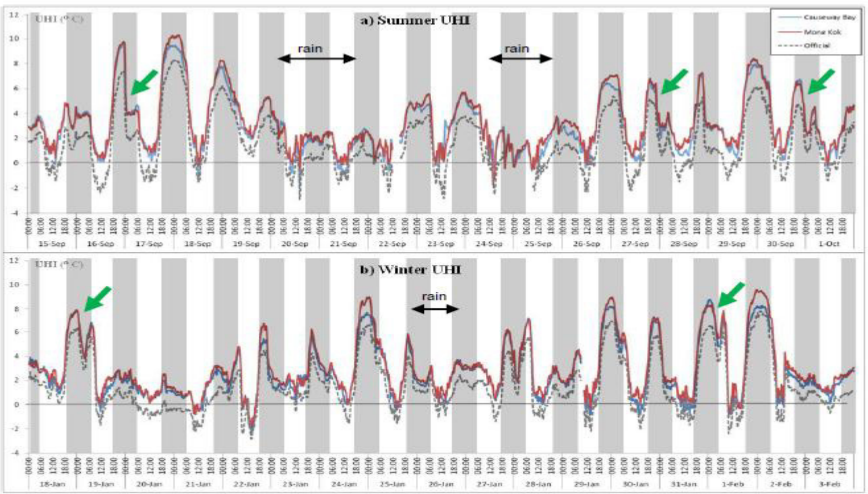

Figure 1: Average UHI_{MK} (red line) and UHI_{CWB} (blue line) against $UHI_{Official}$ (grey dotted line) over 17 consecutive days in (a) summer and (b) winter. The green arrows indicate bimodal peaks.

3.3. Statistical Analyses of UHI

The outcomes of meteorological regression models indicated solar radiation consistently appeared to be the most important contributing factor (rank 1) that had a negative correlation with UHI_{MK} based on all four selection criteria in both seasons. In brief, UHI_{MK} would be weakened as the solar radiation increased. Rank 2 variables of UHI_{MK} were summer temperature and winter humidity, both exhibiting a negative correlation with UHI_{MK}. Results of CWB were slightly different from those of MK. Solar radiation was ranked 3 whereas relative humidity and temperature were ranked 1 and 2 respectively for the summer UHI_{CWB}. All predictor variables had a negative correlation with summer UHI_{CWB}. For winter UHI_{CWB}, solar radiation was the most important predictor with a negative correlation. However, the rank 2 variable was wind direction with a positive correlation with UHI_{CWB}, suggesting that a larger angle away from the 0 ºN direction would increase UHI_{CWB} in the winter.

The outcomes of the environmental regression models indicated greenery density (rank 1) had a negative association with both UHI_{MK} and UHI_{CWB}. The presence of greenery in an urban setting is widely known to have mitigating effects on the UHI [9,10]. Rank 2 were social deprivation index and topography respectively in summer and winter for both areas. The regression results confirmed not only the ameliorating effects of greenery but also impacts associated with topography and social deprivation index. Although the analysis may be spatially and temporally incomplete, the study did assist in better identification of factors impacting local UHI in urban areas of Hong Kong.

4. Conclusion

This study has effectively validated and confirmed the methodological feasibility of deploying a large number of small, durable and inexpensive sensors for widespread measurement of road-side temperature and relative humidity. The regression models have also established statistically potential factors influencing the microclimate UHI across MK and CWB. These findings have benefited urban design and policy management, informing the prevalence of shadings effects from built structures over strong wind advection in street level microclimate studies. This microclimate UHI study can contribute knowledge to studies on quality of life and thermal comfort of urban areas that are expected to be homes to more than two thirds of the world population by 2025.

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