Empirical study on temporal variations of canopy-level Urban Heat Island effect in the tropical city of Greater Kuala Lumpur

Logaraj Ramakreshnan, Nasrin Aghamohammadi, Chng Saun Fong, Amirhosein Ghaffarianhoseini, Li Ping Wong, Nik Meriam Sulaiman

Abstract
A very few studies have evaluated and understood the temporal dynamics of UHI in many expanding tropical cities. Hence, this study investigated the temporal variations of canopy-level UHI in selected urban stations, namely Petaling Jaya (PJ) and Subang (SUB), of Greater Kuala Lumpur (GKL) using 2016’s hourly data set obtained from meteorological observatories. The association between meteorological factors and UHI Intensity (UHII) is evaluated using linear regression models and Pearson correlation analysis. The findings revealed positive thermal contrasts between urban and sub-urban stations with maximum UHII during dry, southwest monsoon season in PJ (June: 1.68 °C) and SUB (August: 1.29 °C) stations respectively. PJ station exhibited a distinct diurnal cycle with the maximum nocturnal UHII of 1.71 °C at about 8 p.m. after sunset under ideal meteorological conditions. The results also demonstrated that UHI events occurred more frequently at nights in urban stations in the magnitude range of 0-2 °C. Cooling at all urban sites starts around 2-3 p.m. with the highest rate of 0.73 °C/h and 0.96 °C/h in PJ and SUB stations. Meanwhile, relative humidity displayed a low positive correlation (r = 0.37, p ≥ 0.05) and a high negative correlation (r = −0.79, p < 0.05) with UHII in PJ and SUB stations respectively. The influence of wind speed on UHII is weak (r = −0.44, p < 0.05) in PJ station and strong (r = 0.83, p < 0.05) in SUB station. Overall, this study can be regarded as one of the comprehensive observational investigations of canopy-level UHI in a tropical city that provide vital inputs to enrich the tropical urban climate literacy.

1. Introduction

In rebuttal to Intergovernmental Panel on Climate Change’s (IPCC) (2007) unsubstantiated assertion of undermining the influence of Urban Heat Island (UHI) on global warming, many researchers have provided substantial evidences of elevated temperatures in the urbanized regions as an unintended consequence of urbanization process (Bhati & Mohan, 2016; Fujibe, 2011; IPCC, 2007). UHI, a phenomenon where the cities are relatively warmer than the sub-urban or rural surroundings is a concomitant impact of human-induced modifications to the surface energy balance of the natural environment (Bejaran & Camilloni, 2003; Čeplová, Kalusová, & Lososová, 2017; Pórolniczak, Kolendowicz, Majkowska, & Czernecki, 2017). In fact, many extensive studies reported UHI as a common phenomenon in most of the cities that evolved over a long period of time (Ahmed et al., 2015; Santamouris, 2015). UHI is most conspicuous under calm and cloudless nights, ephemeral and deemed to be a significant perturbation to urban climate (Acero, Arrizabalaga, Kupski, & Katzschner, 2013; Bottyan & Unger, 2003; Gedzelman et al., 2003). In fact, urbanization process-induced UHI has been propounded as a significant factor of global warming due to observed changes in the decreasing diurnal temperature ranges and declining warming rates of the lower troposphere compared to the surface (Zhou et al., 2004). Contextually, UHI is referring to the elevated air or surface temperatures in cities which can be measured as the temperature differences in comparison to a rural fringes, rather than referring to absolute measures of ambient temperature (de Lucena,
Rotunno, Franca, Peres, & Xavier, 2013). Generally, unprecedented population explosions coupled with urban expansions, which are mainly clustered in the tropical urban agglomerations, exert a potential adverse impact to the exacerbation of UHI. Other than this, a number of factors are attributable to this phenomenon such as city size and morphology, topography, climate zones, meteorological conditions, urban materials and air pollution (Acero et al., 2013; Chow & Roth, 2006; Ivajnić, Kaligaric, & Žiberna, 2014; Kim & Baik, 2005; Oke, Johnson, Steyn, & Watson, 1991; Zhang et al., 2013). At the human level, modifications in thermal, radiative and aerodynamic properties of the Earth’s surface can negatively impact the urban communities’ health, thermal comfort, and lifestyle (Acero et al., 2013; Bejaran & Camilloni, 2003; Chun & Guldmann, 2014; Hart & Sailor, 2009; Morris, Simmonds, & Plummer, 2001). In a bigger scale, this phenomenon aggravates regional atmospheric pollution, ecological cycles, weather events and energy consumption (Bhati & Mohan, 2016; Hart & Sailor, 2009).

UHIs are of several types such as atmospheric UHI, surface UHI and modelling/simulated UHI which can be distinguished based on their study approaches (Guo et al., 2015; Mason, 2006; Voogt & Oke, 2003). Particularly, atmospheric UHI can be defined based on different layers of the atmosphere (canopy and boundary layers) from where the measurement was conducted (Kothakar & Bagade, 2018; Ramakreshnan et al., 2018; Voogt & Oke, 2003). Canopy-layer UHI is usually detected at human-height levels by on-site measurements using stationary or mobile weather station networks whereas boundary-layer UHI requires specialized sensor platforms such as tall towers or aircraft-mounted instruments (Voogt & Oke, 2003). Essentially, assessment on the nature and attributes of canopy-layer UHI with sensors positioned in the midst of urban complexities is still indispensable compared to the other methodological approaches as it enables a direct measure of the cascading impacts of temperature amplifications on urbanite’s health and physical geography.

1.1. Greater Kuala Lumpur (GKL) as an emerging metropolitan hub in south-east Asia

Similar to many south-east Asian megacities, GKL suffered in- evitable territorial development while hosting one-fifth of the current urban population of Malaysia. Being a dynamic geopolitical region in the heart of south-east Asia, GKL is envisaged to spur the country’s economic growth by leveraging upon its strengths on a cosmopolitan population and world-class infrastructure as espoused in Malaysian Tenth Plan (EPU, 2010). Indeed, its strategic location at the centre of the trade route between China and India, and next to the Straits of Malacca, established GKL to be the nexus of economic and social activities that contributes about 41% of the country’s Gross Domestic Product (GDP). Due to a notable role as addressed in Malaysian policies, GKL and the other townships within the conurbation observed an overwhelming economic and human capital development which has led to a surge in population density and urban growth footprints as depicted in Fig. 1. As a result, high population growth mandate the satellite towns in the conurbation to expand both vertically and horizontally while imposing greater impact on local urban climate, often manifested in the form of UHI (Amanollahi, Tzanis, Ramli, & Abdullah, 2016; Shaharuddin, Noorazuan, Takeuchi, & Noraziah, 2014; Yusuf, Pradhan, & Idrees, 2014).

1.2. Overview of UHI assessments and their methodological critiques in GKL

Despite a limited number of studies, local scientists have still dedicated substantial work to investigate and understand the nature of Malaysian UHI to predict its characteristics for mitigation purposes. As highlighted in a comprehensive review of local UHI assessments by Ramakreshnan et al. (2018), a very limited number of studies, especially those conducted before 2004, have utilized on-site monitoring approaches to investigate canopy-level UHI phenomenon by deploying stationary or mobile weather stations for real-time data collection (Elayed, 2012; Sani, 1972, 1984, 1986, 1987, 1991). However, these studies used datasets of limited temporal resolutions to elucidate the generation and development of UHI in their respective study areas. Nevertheless, there are no studies in GKL have evaluated the temporal dynamics of canopy-level UHI Intensity (UHII) over annual, seasonal or diurnal scales that usually require big datasets collected over a long-term observational period. Hitherto, the range of timing where the maximum UHII can be reached remains unanswered in the local context. Emerging studies often overlook the importance of obtaining a complete picture of the spatial and temporal development of UHI while developing adaptation and mitigation plans, which is a prerequisite to efficiently target the strategies and resources for the evidence-based mitigations. Besides this, contemporary studies delineate a progressive trend towards the application of advanced modelling, simulation (Morris et al., 2015, 2016, 2017) and satellite technology (Amanollahi et al., 2016; Hashim, Ahmad, & Abdullah, 2007; Salleh, Latif, Mohd, & Chan, 2013; Shaharuddin, Noorazuan, & Yaakob, 2009, 2014; Yusuf et al., 2014) in local UHI assessments. However, it should be understood that each of these methodological approaches in the empirical studies are presenting different types of UHIs as discussed earlier in the previous section. Moreover, each of these methodological approaches certainly have their strengths and weaknesses. Remotely sensed data, while offering good spatial coverage of surface UHI, is still lacking in temporal details. According to Bassett et al. (2016), satellite-derived surface UHI is incomparable with canopy-layer UHI due to heat advection effects of wind. Furthermore, surface skin temperature measured through remote sensing images is incomparable to near-surface air temperature that correlates more to human comfort levels (Wang, Huang, Fu, Atkinson, & Zhang, 2016). On the other hand, Mirzaei (2015) discussed that models and simulations have limitations in integrating a series of complex phenomena occurring in cities and in avoiding unrealistic assumptions. By considering this, in-situ measurements using permanent weather stations are still effective in providing long-term temporal coverage of canopy-level UHI phenomenon and comparison between complex phenomenon happen in the urban canyons and UHI. In spite of their vitality in providing real-time data with better temporal resolution, in-situ measurements are also essential to serve as a baseline/reference data for validation of the results produced by the simulation and remote sensing technologies (Ramakreshnan et al., 2018).

1.3. Overview of UHI factors evaluated in GKL and other climate regions and the existing research gaps

A number of studies are devoted to investigating the contributing factors of UHI in the local context. Reduction in vegetation cover (Buyadi, Mohd, & Misni, 2013a, 2013b), land-use changes (Salleh et al., 2013; Thanir, Mohamad, & Abdullah, 2013), urban landscape morphology (Thani et al., 2013) and climate change (Salleh et al., 2013) are postulated as the most significant factors of UHI in GKL. While UHI can be associated with both urban and meteorological factors, it is apparent that the aforementioned studies only examined the influence of urban factors on the development and intensification of UHI in GKL. This created a research gap for the upcoming study to explore the influence of meteorological factors on urban heating phenomenon. Moreover, meteorological variables which are localized to specific climate and geographical locations need to be given similar weightage to elucidate their association with UHI phenomenon. Table 1 illustrates the findings of some studies which have evaluated the influence of selected meteorological factors on UHI effect using real-time data in different climate zones.

In a glance, while wind speed and cloud cover become the mostly investigated meteorological variables, a plethora of studies are concentrated in temperate and continental climate zones only. Although the influence of meteorological factors on UHI is salient, studies in
tropical climates are still scanty and more scholarly studies within hot and humid climates are required to enrich the persisting knowledge gap. Hence, GKL could be an ideal tropical destination to examine the meteorological factors’ influence on UHI effects in a local context.

By considering all the existing research and knowledge gaps, the current study attempted to investigate the temporal variations of canopy-level UHI and its association with meteorological variables in the selected study areas in GKL using meteorological data collected from Malaysian Meteorological Department (MetMalaysia) over a one-year period of time. In contrast with previous measurements, this study exhibits novelty in contributing a detailed overview of the long-term temporal dynamics of UHII at both diurnal and seasonal scales, a comprehensive understanding on the hourly cooling rates of tropical urban stations as well as the interaction between selected meteorological variables and the behaviour of urban heat in GKL. This study is essential to understand the temporal variations of UHI in megacities like GKL for a comprehensive apprehension on how urbanization influences the thermal regime of well-developed urban areas within the conurbation. At the same time, an in-depth comprehension of the temporal variability of UHI is essential to ensure an effective and coherent development of evidence-based adaptation and mitigation strategies for the improvement of urban thermal environment.

2. Data and method

2.1. General description of study area

GKL (3° 09′N; 101° 44′E), also known as Klang Valley, is a megapolis that comprises the Federal Territory of KL and its surrounding municipalities as illustrated in Fig. 2. It covers 8236 km² area in the southern part of Malaysia (Morris et al., 2017). It experiences tropical rainforest climate (Köppen-Geiger: Af) with annual hot and humid climatic conditions and heavy tropical rains due to its proximity to the Earth’s equator (Aflaki et al., 2016; Peel, Finlayson, & McMahon, 2007). Located 21 m above the mean sea level, it is characterized by near-uniform monthly mean temperature (26.8–27 °C) and high mean relative humidity (63–68%) (Morris et al., 2017). In parallel to the aspiration of GKL to be one of the top 20 world-class liveable cities that

Table 1

<table>
<thead>
<tr>
<th>Study</th>
<th>Location</th>
<th>Climate</th>
<th>Method</th>
<th>Atmospheric Layer</th>
<th>Meteorological factors</th>
<th>Correlation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Klysik and Fortuniaik</td>
<td>Lodz, Poland</td>
<td>Continental</td>
<td>WS</td>
<td>UCL</td>
<td>Wind speed</td>
<td>–</td>
</tr>
<tr>
<td>Morris et al. (2001)</td>
<td>Melbourne, Australia</td>
<td>Temperate</td>
<td>WS, Regression</td>
<td>UCL</td>
<td>Wind speed</td>
<td>–</td>
</tr>
<tr>
<td>Chow and Roth (2006)</td>
<td>Singapore</td>
<td>Tropical</td>
<td>WS</td>
<td>UCL</td>
<td>Wind speed</td>
<td>–</td>
</tr>
<tr>
<td>Liu et al. (2007)</td>
<td>Beijing, China</td>
<td>Continental</td>
<td>WS</td>
<td>UCL</td>
<td>Relative humidity</td>
<td>–</td>
</tr>
<tr>
<td>Camilloni and Barrucand (2012)</td>
<td>Buenos Aires, Argentina</td>
<td>Temperate</td>
<td>WS</td>
<td>UCL</td>
<td>Wind speed</td>
<td>–</td>
</tr>
<tr>
<td>Wong et al. (2016)</td>
<td>Hong Kong</td>
<td>Temperate</td>
<td>WS</td>
<td>UCL</td>
<td>Solar radiation</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Temperature</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Relative humidity</td>
<td>–</td>
</tr>
</tbody>
</table>

*a WS = Weather Stations.

*b UCL = Urban Canopy Layer, UBL = Urban Boundary Layer.
generate substantial remuneration for the national income (Chuen, Karim, & Yusoff, 2014), a higher rate of urbanization is predicted in near future, catalysed by infrastructure developments, urban migrations and better career prospects. GKL experiences two main seasons including the wet, northeast monsoon (November–March) and the dry, southwest monsoon (June–September) with two relatively shorter inter-monsoon periods between the above-mentioned monsoons (Aflaki et al., 2016; Satari, Zubairi, Hussin, & Hassan, 2015). However, GKL presumed to be less affected by the exact intensity of both monsoon winds due to its strategic geographical location in the middle of Sumatra island (southwest) and Titiwangsa (northeast) mountain range that provides shielding effect from the prevailing monsoon winds (Ooi, Chan, Subramaniam, Morris, & Oozeer, 2017). These unique geographical criteria make the temporal, particularly seasonal canopy-level UHI assessment in GKL, more interesting and vital to be compared with the characteristics of other tropical UHIs.

2.2. Description of observation sites and meteorological observatories of MetMalaysia

The conventional approach in site selection for UHI studies is that one or more urban stations will be chosen and their average air/surface temperature will be compared with the air/surface temperature of a reference rural station (Stewart & Oke, 2012). However, a number of
researchers argued that this concept is not restricted to urban-rural temperature discrepancy only, rather covered a wide range of diversified ideas such as temperature comparison between areas of different degrees of development, growth or maturation (Ezber, Lutfi Sen, Kindap, & Karaca, 2007; Memon, Leung, Liu, & Leung, 2011). In addition, selection of a rural station can be difficult in certain regions that underwent a rapid urbanization. In fact, the existing smaller pockets of rural areas in such region can be contaminated with pre-urban conditions that do not provide a better representation of rural climatological attributes. This is also the case of GKL whereby the term rural does not fit most of the vernacular GKL landscapes. By considering this, this study selected SEP, a sub-urban station, which is located approximately 45 km far from the densely-urbanized cluster of GKL as shown in Fig. 2(C), as a reference station to be compared with the other two urban stations, such as PJ and SUB stations. Furthermore, SEP station is sparsely-built and still retains a significant proportion of vegetation cover and permeable surface cover, which is a relatively different landform compared to the other urban stations. Fig. 3 demonstrates the aerial view and landscape view photographs of the study sites representing contrasting surface morphologies.

PJ station and SUB stations portray almost similar landscape structure with the majority of low- (1–3 storeys: 3–9 m) and mid-rise (4–9 storeys: 12–27 m) buildings interspersed with fewer numbers of high-rise (< 9 storeys: < 27 m) buildings. On the other hand, SEP station represents a different land cover with a significant portion of pervious, vegetated landscape that enable it to be chosen as a reference sub-urban station. According to Local Climate Zones (LCZ) scheme (Stewart & Oke, 2012), field observations revealed that both PJ and SUB stations represent a hybrid between compact low- and mid-rise built types whereas SEP station is sparsely-built and dispersed with dense vegetation. The land cover is mostly paved with asphalt, tar, and bricks in both urban stations whereas sub-urban station consists of a sparse arrangement of low- and mid-rise buildings in a natural (vegetated) setting. The metadata of study sites is presented in Table 2.

Other than this, there are some additional criteria for the inclusion of these particular zones in this study. Firstly, all these three stations consist of a simultaneously-operating integrated Automated Principal Weather Stations (APWS) of MetMalaysia which are designed in compliance with the World Meteorological Organization (WMO) and the International Civil Aviation Organization (ICAO) standards to fulfill international requirements for weather and climate monitoring. Secondly, meteorological variables are observed at the same time using instruments of similar range and resolutions for reliable comparisons to be made. Table 3 shows the description of the instruments used in data collection in the three meteorological observatories.

In particular, these three meteorological observatories are deployed with calibrated sensors to collect meteorological parameters at a height of 1.5 m above ground, except for PJ station which is relocated on a rooftop of a four-story building (approximately 10 m) since early 2000. According to Jarraud (2008), such height is more than WMO’s recommendations to site the meteorological instruments. However, studies by Chow and Roth (2006) and Oke (2004) clarified that temperature gradient errors should be negligible for the sensors placed more than 1 m height from the surface in densely built-up urban stations. In regard to this, assumptions are made that PJ station which satisfies similar urban morphology of the urban sites included in the aforementioned studies to display no vertical temperature gradients. To clarify this, vertical temperature gradient measurements are conducted in the PJ station’s site from 12 p.m. to 2 p.m. and a very minimal mean temperature gradient of 0.035 °C per meter was recorded. In addition, the building rooftop where the instruments are located covered with EPDM rubber (ethylene-propylene-diene monomer (M-class) rubber) to insulate and minimize heat exchange with the interior of the building. Thirdly, the stations are ensured to have minimal altitude variations to eliminate the influence of terrain differences on air temperature under the standard environmental lapse rate (0.64 °C drop per 100 m increase

<table>
<thead>
<tr>
<th>Station</th>
<th>Coordinates</th>
<th>Altitude (m)</th>
<th>LCZ attributes</th>
<th>Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>PJ</td>
<td>3°6’55.0” N; 101°37’41.4” E</td>
<td>60.80</td>
<td>Hybrid between compact low- and mid-rise buildings, interspersed with some high-rise buildings.</td>
<td>Interspersed with some high-rise buildings.</td>
</tr>
<tr>
<td>SUB</td>
<td>3°56’07.9” N; 101°32’38.8” E</td>
<td>16.64</td>
<td>Hybrid between compact low- and mid-rise buildings, interspersed with some high-rise buildings.</td>
<td>Interspersed with some high-rise buildings.</td>
</tr>
<tr>
<td>SEP</td>
<td>2°43’50.9” N; 101°42’11.5” E</td>
<td>16.11</td>
<td>Sparsely-built with dense vegetated area.</td>
<td>Sparsely-built with dense vegetated area.</td>
</tr>
</tbody>
</table>

Table 2: Metadata of study sites within 5 km radius from the meteorological observatories of MetMalaysia.
in altitude) (Siu & Hart, 2013). Since the altitude variations of the three stations are very small within 16–60 m, no empirical temperature corrections are performed in this study. Fourthly, the general land use within a radius of 500 m, from where the meteorological observatories are located, did not vary significantly in these stations which represent the local-scale microclimate of that particular land use.

2.3. Meteorological data and time period justifications

Hourly (MYT: Malaysia Local Standard Time) meteorological data such as air temperature, relative humidity, wind speed and direction, atmospheric pressure and rainfall of the year 2016 are obtained from MetMalaysia for UHI analysis. The year 2016 is of particular interest in this study as GKL encountered many devastating consequences of rising temperatures such as flash floods, heat waves and even rare episodes of hail storms, which justify the imperative need of current study to evaluate the status of temporal UHI of this year (Akasah & Doraisamy, 2014; Othman et al., 2016; The Star, 2016). Adding to this, United Nation declared 2016 as the hottest year ever on record after observing the mean global temperature of the first-half of the year to be 1.3 °C warmer than the late nineteenth century (UN (United Nations), 2016). Therefore, this study analysed 2016’s temperature profile and inherent UHII of the selected urban stations in GKL.

2.4. Data management and statistical analyses

In reference to Velazquez-Lozada, Gonzalez, and Winter (2006), meteorological datasets acquired under ideal meteorological conditions (87 calm and clear days in all the urban and sub-urban stations in a year) are only included in UHI analysis to avoid synoptic scale effects. Therefore, meteorological dataset recruited from MetMalaysia are processed by manually excluding the days with rainfall and moderate to strong winds (> 6.00 m/s) according to Beaufort’s scale, a widely used empirical measure to analyse and interpret the wind speed (Met Office, 2016). As described by Wang et al. (2016) and Yang, Zhang, and Qian (2012), wet days are not included due to differences in heat fluxes between rainy and dry days. The hourly meteorological data collected on clear and dry days with stable atmospheric conditions (no abrupt changes in the local weather) in both urban and sub-urban stations are utilized to examine the temporal profile of UHI. Besides this, ambiguous data such as missing values, default values and deviated values from the observed ranges are excluded in the analysis. The cleaned and processed data are used to compute hourly and monthly averages of relevant meteorological variables for the year 2016. For diurnal UHII computation, the one-year average hourly air temperature of the suburban station (SEP) was subtracted from that of the urban stations (PJ and SUB). Similarly, seasonal UHII was calculated by subtracting monthly average air temperature of the sub-urban station (SEP) from that of the urban stations (PJ and SUB). The Eq. (1) (Liu, Ji, Zhang, Ji, & Zheng, 2007) is used to calculate UHII:

$$UHII = T_{suburban} - T_{sub-urban}$$

where,

$$T = \text{Average air temperature.}$$

As expounded by Oke (1982), cooling/warming rates of both urban and sub-urban stations are important indicators that drive the diurnal cycles of UHI. Hence, Eq. (2) is used to calculate hourly cooling rates of both urban and sub-urban stations in this study:

$$\text{Hourly cooling rate} = \frac{\Delta T_{t-2}}{\Delta T_{t-1}} = \frac{\text{Average air temperature differences between first and second observations}}{\text{Time differences between first and second observations.}}$$

Further investigation on the possible influence of selected meteorological variables such as wind speed and relative humidity on UHII has been carried out by performing regression and bivariate Pearson correlation analysis in IBM SPSS statistics version 20. 95% confidence interval and two-tailed test of significance are selected. The direction and strength of association between independent and dependent variables are interpreted using the guide provided by Mukaka (2012).

3. Results and discussion

As the temporal variation of UHIII is modulated by meteorological conditions (Mathew, Khandelwal, & Kaul, 2016), this study will initially present a descriptive analysis of average meteorological conditions observed in the respective urban and sub-urban stations in the year 2016. Thereafter, a detailed analysis of the temporal dynamics of UHII over seasonal and diurnal scales as well as the influence of selected meteorological variables on UHII will be discussed.

3.1. Temporal analysis of meteorological variables in urban and sub-urban stations in GKL

The temporal evolution of average air temperature and average relative humidity in two urban stations, PJ and SUB, in comparison to the reference sub-urban station, SEP is illustrated in Fig. 4. In general, the average air temperature and average relative humidity of all the stations exhibit similar trends in seasonal and diurnal variations respectively, indicating a clear and strong temporal distinction.

The amplitude difference of seasonal average air temperature and average relative humidity is significant between the urban and sub-urban stations, especially during the dry period associated with the southwest monsoon season. This indicates that both urban stations are relatively warmer and drier than the sub-urban station. PJ station, a vibrant site encapsulated by the north, west and east roads and also in the proximity to the busy Federal Highway as depicted in Fig. 5, always recorded the maximum average temperatures throughout the year, with the highest magnitude of 30.97 °C observed during the onset of pre-southwest monsoon season. Persistence of high air temperatures in PJ station could be attributed to higher anthropogenic heat and emission loads liberated from vehicular exhausts and massive road infrastructures that trap and insulate the heat within the built environment. Adding to this, both urban stations recorded the maximum temperatures between the ranges of 33.10–33.38 °C during late afternoon hours (2–4 p.m.), where intense vehicle use is observed. Conversely, SEP station recorded the minimum average temperatures in all the consecutive months which is plummeted on November (27.36 °C).

On the other hand, pre-southwest and northeast monsoon seasons (especially at the end of the year) registered maximum average relative
humidity assemblages which can be associated with heavy monthly rainfall records in both seasons for all the stations as shown in Fig. 6.

In contrast to the urbanized PJ station, SEP station, which retains a big portion of natural vegetation, recorded the highest average relative humidity values throughout the year. In terms of diurnal variations, urban areas are warmer than the sub-urban area before sunrise and in the late afternoon. Ironically, a very minute temperature difference is observed between urban and sub-urban stations from 9.00 a.m. until 12.00 p.m. SEP station, which is sparsely-built, is directly exposed to the intense solar radiation after the sun rises and gets warmer at the same rate as the urban stations. However, the heat loss (cooling rate) in SEP station starting from the late afternoon and consecutive hours is greater due to more open and exposed land structure compared to compactly built-up urban stations. Lacking thermally-bulk concrete and man-made structures, pervious surfaces and reduced anthropogenic emissions in SEP station enable it to release the solar radiation at a

Fig. 4. Variation of average air temperature and relative humidity in the selected urban and sub-urban stations of GKL: (A) Average air temperature variations on a seasonal scale; (B) Average relative humidity variations on a seasonal scale; (C) Average air temperature variations on a diurnal scale; (D) Average relative humidity variations on a diurnal scale.

Fig. 5. Enlarged aerial view of PJ station which is located in the middle of the busiest heavy road network.
faster rate. Dense concrete jungles of both PJ and SUB stations trap the incoming solar radiation during the day and re-radiate it at nights, initiating the on-set of UHI phenomenon. Apart from this, the average temperature is inversely related to the average relative humidity as portrayed in Fig. 4(C) and (D). A gradual decline in average relative humidity is observed with increasing average temperatures, which starts about an hour after sunrise in all the stations. After that, the average humidity started to increase prior to a drop in the average temperature in the late afternoon, as observed at 3.00 p.m. The seasonal and diurnal profile of wind pattern is displayed in Fig. 7 by highlighting the speed and frequency of wind blowing from respective cardinal directions.

By referring to modern Beaufort’s scale (Met Office, 2016), PJ, SUB and SEP stations experience 99.30%, 93.80% and 88.50% episodes of calm winds (\( \leq 4.00 \text{ m/s} \)) respectively during the northeast monsoon season, with the prevailing winds from the northeast, except for SUB station. The wind is mostly blowing from the northwest direction in SUB station. During the southwest monsoon season, the calm wind is predominantly blowing from the southeast direction in all the stations (PJ:80.30%, SUB:93.20%, SEP:96.10%) at speeds between 0–4.00 m/s. Overall, approximately more than 90% of the wind from all these stations are relatively calm (0–4.00 m/s) under stable atmospheric conditions. Meanwhile, there is an irregular wind pattern observed during both short inter-monsoon seasons. On the diurnal scales, the similar periodic behaviour is observed in all the stations. SEP station always record the highest wind speed among the three stations in all the four monsoon seasons, especially before sunrise and after sunset. Apparently, higher wind speed is always observed in SUB station compared to SEP station during late afternoon before continue to decrease after the sunset. Conversely, PJ records the lowest wind speed during all the seasons compared to the other two stations. As indicated in Fig. 8, seasonal average wind speed ranges between 1.00–2.50 m/s in all the stations. As discussed by Park (1986) and Santamouris (2015), the average wind speed in both urban and sub-urban stations are lower than the reported threshold wind speeds (4.00–11.00 m/s) that able to decrease the UHI. Essentially, the average wind speeds in all the selected zones are mostly calm and gentle which ensure the feasibility of most of the data sets to be incorporated in the UHI analysis in the later part.

### 3.2. Temporal variations of canopy-level UHII in GKL

#### 3.2.1. Seasonal variation of canopy-level UHII in GKL

The perceptible positive thermal contrast between urban stations and sub-urban station under ideal synoptic weather conditions as illustrated in Fig. 9, corroborates the genesis of UHI effect with varying intensities in this study.

Both urban stations display almost similar seasonal trends. Indeed, PJ station records the highest UHII in every month compared to SUB station. The range of UHII for PJ station is within 0.74–1.68°C whereas for SUB station is within 0.16–1.29°C. Specifically, the maximum average UHII are usually observed during relatively drier months associated with southwest monsoon seasons from June to August for both PJ (June: 1.68°C) and SUB (August: 1.29°C) stations. Even so, there is an obvious UHII fluctuation registered during this period where a steep drop is observed between June and July before it rises again in August. Interestingly, an inverse fluctuating relationship (negative correlation) is observed among relative humidity (Fig. 4B), wind speed (Fig. 8) and season intensities in this study. The perceptible positive thermal contrast between urban stations and sub-urban station under ideal synoptic weather conditions as illustrated in Fig. 9, corroborates the genesis of UHI effect with varying intensities in this study.

Both urban stations display almost similar seasonal trends. Indeed, PJ station records the highest UHII in every month compared to SUB station. The range of UHII for PJ station is within 0.74–1.68°C whereas for SUB station is within 0.16–1.29°C. Specifically, the maximum average UHII are usually observed during relatively drier months associated with southwest monsoon seasons from June to August for both PJ (June: 1.68°C) and SUB (August: 1.29°C) stations. Even so, there is an obvious UHII fluctuation registered during this period where a steep drop is observed between June and July before it rises again in August. Interestingly, an inverse fluctuating relationship (negative correlation) is observed among relative humidity (Fig. 4B), wind speed (Fig. 8) and rainfall (Fig. 6) between June to August, indicating a possible relationship between these meteorological variables and UHII in these urban stations. The minimum UHII are usually observed during wet, northeast monsoon season between December and January in both urban stations. Though little, the seasonal UHII trend observed in this study commensurate with the results obtained by the previous studies conducted in other tropical regions characterized by hot and humid climatic conditions. For instance, Chow and Roth (2006) observed highest UHI magnitude (7.07°C) within commercial areas during dry, southwest monsoon season in Singapore. Similarly, Amorim and Dubreuil (2017) identified highest UHII (4.1°C) during the drier months of April and July with lowest precipitation records in Brazil. Interestingly, high UHII are also recorded during dry, summer nights in some upper latitude countries of cold climates. For instance, Klysik and Fortuniak (1999) observed greatest UHII between 3 and 4°C to occur during summertime in Lodz, Poland. Likewise, Kolokotroni and Girdharan (2008) witnessed high daytime UHII of 8.9°C under ideal synoptic weather conditions in the semi-urban area of London in summer. Even though highest seasonal UHII are usually recorded during the hot and dry seasons in both climates, the intensities recorded in this study are relatively lower compared to the aforementioned studies.

![Fig. 6. Monthly variations of average rainfall in the selected urban and rural sites of GKL.](image-url)
3.2.2. Diurnal variation of canopy-level UHII in GKL

Both urban stations registered positive hourly average maximum UHII that indicates the air temperature at urban stations always higher compared to the sub-urban station as shown in Fig. 10.

In particular, PJ station mostly recorded high average UHII with a maximum value of 1.71 °C at about 8 p.m. after sunset. Conversely, SUB station exhibits a contrasting diurnal pattern compared to PJ station where an increasing trend of UHII is observed after sunrise until 4 p.m.
before declining in the late afternoon. In fact, the variation of UHII amplitudes between both urban stations is noticed to be very large between the range of 0.74–1.10 °C, especially before sunrise and after sunset. Such a big difference in UHII between these urban stations at nights and early mornings can be attributed to varying degrees of urban metabolism and traffic activities in both stations. As discussed earlier, a meteorological observatory in PJ station which is located in the adjacent of a heavy network of busy roads with unceasing traffic activities until late night accumulates and concentrates anthropogenic heat and smoke exhausts from vehicular emissions that can be possibly related to the amplification of the air temperature around the station. Meteorological observatory of SUB station is designated for aviation purposes and located in an open space, little far from the compact building structures concentrated in the centre of SUB station. Such physical land structure which is quite different from that of PJ meteorological observatory could cause the observed variations among the UHII recorded in these urban stations. However, this range seems to be smaller during the daytime, approximately one hour after the sunrise until late afternoon. As displayed in Fig. 11, the cooling rate of SUB station is higher than PJ station in the late afternoons and nights.

In response to this, SUB station tend to release heat faster than PJ station, justifying the possible reasons for the smaller nocturnal UHII compared to PJ station. Basically, peak UHII values are observed at late evening few hours before or after the sunset, indicating that the UHI phenomenon tends to be nocturnal. As observed in Fig. 11, cooling at all urban sites starts around 2–3 p.m., slightly later than that observed at the rural station. From this, it can be clearly inferred that the growth of UHI occurs as SEP station cools at higher rates than those observed at urban sites from late afternoon until sunset. The diurnal UHI attains a maximum intensity when rural and urban cooling rates become equal in magnitude around one hour after sunset for PJ station and around late afternoon for SUB station. After sunrise, SEP experiences much higher warming compared to the urban stations, which results in a rapid decrease of UHI intensity throughout the morning hours. In this study, hourly cooling rates in both urban stations are comparatively steady from the night (9 p.m.) until early morning (6 a.m.) as also reported in the neighbouring tropical country, Singapore, by Chow and Roth (2006) using similar approaches. In addition, the highest urban cooling
rates recorded in PJ station (0.73 °C/h) and SUB station (0.96 °C/h) are approximately similar to the one observed in Singapore and proportionately smaller than the one observed in another tropical city, Mexico (1.8 °C/h) (Jauregui, 1986). Such disparities in urban cooling rates between climatically similar cities in different geographical zones, reminiscent the influence of topography, elevation and corresponding synoptic meteorological elements on heat dissipation from the urban areas. This area still needs more scholarly studies to provide in-depth insight into the influence of geographical features on the urban heating phenomenon.

3.2.3. Frequency distribution of the UHII classes in GKL

As most of the peak UHII in urban stations are observed at late evenings, this section evaluated frequency distribution of hourly UHII at both daytime (7 a.m.-7 p.m.) and night-time (7 p.m.-7 a.m.). As illustrated in Fig. 12, the temperature differences between the urban stations and its sub-urban surrounding are evenly distributed among the considered UHII groups during both daytime and night-time.

Night-time UHI effect is the highest compared to the day time effect, and this finding is consistent with the theory of urban energy balance discussed by Oke (1988) and corroborates that UHI is a nocturnal phenomenon (Kim & Baik, 2002; Van Hove et al., 2015). However, a greater number of nocturnal UHI events of PJ station are within 1–2 °C, which is higher compared to SUB station (0–1 °C). Nevertheless, SUB station also recorded high daytime UHII which tally with the findings of Amorim and Dubreuil (2017) who observed the occurrence of highest UHII during the day-time in tropical settlements of Brazil.

3.3. Association between selected meteorological variables and UHII in GKL

Linear regression and Pearson correlation analyses are performed to explore the influence of synoptic meteorological variables such as relative humidity and wind speed on temporal UHII. Besides, the relationship between average hourly changes of relative humidity and
wind speed on the average hourly changes of UHII is also investigated. The outcomes of the linear regression analysis which are statistically significant at \( p < 0.05 \) for both PJ and SEP stations are displayed in Fig. 13.

The results of regression equations, Pearson correlation and regression coefficients of the corresponding meteorological variables and UHII is tabulated in Table 4.

In PJ station, relative humidity demonstrated no significant linear relationship and a low positive correlation with UHII (\( r = 0.37, p \geq 0.05 \)), indicating that only 0.1 °C of UHII will increase for every one unit increase in the mean relative humidity (+1%). Likewise, hourly change in UHII (\( \Delta UHII \)) and relative humidity (\( \Delta RH \)) also revealed low positive correlation in PJ station (\( r = 0.49, p < 0.05 \)). Surprisingly, this study highlighted a contrasting finding compared to the past studies which identified a negative correlation between relative humidity and UHII (Kim & Baik, 2002; Liu et al., 2007; Wong, Lai, Low, Chen, & Hart, 2016). However, a comparative study by Liu, You, and Dou (2009) in a monsoon-influenced humid continental climate zone (Beijing) showed a positive association between relative humidity and temperature during winter due to the use of an urban heating system.

### Table 4

<table>
<thead>
<tr>
<th>Regression variables</th>
<th>Stations</th>
<th>Regression equations</th>
<th>( R^2 )</th>
<th>( r/p )</th>
</tr>
</thead>
<tbody>
<tr>
<td>UHII, RH, WS</td>
<td>PJ</td>
<td>UHII = 0.0147 RH + 0.1189</td>
<td>0.14</td>
<td>0.37 / p = 0.075</td>
</tr>
<tr>
<td></td>
<td></td>
<td>UHII = −0.3338 WS + 1.5268</td>
<td>0.20</td>
<td>−0.44 / p = 0.030</td>
</tr>
<tr>
<td></td>
<td>SUB</td>
<td>UHII = −0.012 RH + 1.4352</td>
<td>0.62</td>
<td>−0.79/p = 0.00</td>
</tr>
<tr>
<td></td>
<td></td>
<td>UHII = 0.1466 WS + 0.3287</td>
<td>0.69</td>
<td>0.83/p = 0.00</td>
</tr>
<tr>
<td>( \Delta UHII, \Delta RH, \Delta WS )</td>
<td>PJ</td>
<td>( \Delta UHII = 0.0277 \Delta RH − 0.0016 )</td>
<td>0.24</td>
<td>0.49 / p = 0.019</td>
</tr>
<tr>
<td></td>
<td></td>
<td>( \Delta UHII = −0.5398 \Delta WS − 0.0136 )</td>
<td>0.30</td>
<td>−0.55 / p = 0.0072</td>
</tr>
<tr>
<td></td>
<td>SUB</td>
<td>( \Delta UHII = −0.0089 \Delta RH − 0.0061 )</td>
<td>0.14</td>
<td>−0.37 / p = 0.098</td>
</tr>
<tr>
<td></td>
<td></td>
<td>( \Delta UHII = −0.0627 \Delta WS − 0.0077 )</td>
<td>0.06</td>
<td>0.25/p = 0.28</td>
</tr>
</tbody>
</table>

RH = Relative humidity; WS = Wind speed; \( \Delta \) (delta) = hourly changes.
that exudes water vapour into the air. While there is a possibility for a positive association between these variables due to the man-made influences, the current study could not find any additional data to support the observations. On the other hand, SUB station illustrated a high negative (strong) correlation between relative humidity and UHII ($r = -0.79, p < 0.05$), in agreement with the findings of the previous studies. As clarified by Kim and Baik (2002) and Liu et al. (2007), evaporation process in drainage-efficient urban surfaces elevates the relative humidity due to an increase in water vapour pressure and a decrease in saturation water vapour pressure. In response to this, the surface air temperature or UHII decreases due to evaporative cooling effects. Thus, the UHII tend to decrease as the relative humidity increases. However, the correlation between hourly change in UHII ($\Delta$UHII) and relative humidity ($\Delta$RH) is weak ($r = -0.37, p \geq 0.05$). Every 1% hourly changes in relative humidity will contributes to 0.02 °C hourly changes of UHII in SUB station.

In PJ station, a low negative correlation ($r = -0.44, p < 0.05$) between average wind speed and UHII although there is no linear relationship observed. The resultant regression equation shows that one unit increase (+1 m/s) in the wind speed would decrease UHII by 0.33 °C. This effect is even greater ($r = -0.55, p < 0.05$) between hourly change in UHII ($\Delta$UHII) and wind speed ($\Delta$WS) where one unit of hourly change (+1 m/s) in wind speed would cause about 0.54 °C hourly changes in UHII in PJ station. These findings are in agreement with Klyzik and Fortuniak (1999) (Poland), Morris et al. (2001) (Australia), Kim and Baik (2005) (Seoul), Chow and Roth (2006) (Singapore) and Memon and Leung (2010) (Hong Kong) who observed a significant negative correlation between wind speed and UHII in regions of different climate zones. In contrast to this, SUB station exhibits a very strong positive relationship ($r = 0.83, p < 0.05$) between wind speed and UHII. In one of the UHI assessments in Melbourne, Morris et al. (2001) revealed that higher cloud cover over certain areas make the wind speed to impose lesser influence on the magnitudes of Melbourne's UHI. While the influence of other meteorological and urban parameters could be a possible explanation for this relationship, this study have no such data to discuss on the contrasting behaviour between UHII and wind speed in SUB station. However, the relationship between hourly changes of wind speed and hourly changes of UHII is negligible ($r = 0.25, p \geq 0.05$) in SUB station.

4. Conclusion

The current study is a primary attempt to evaluate temporal variations of canopy-level UHII over seasonal and diurnal scales in the selected urban stations (PJ & SUB) of GKL in reference to a less developed sub-urban station (SEP). In a broader perspective, observations by few meteorological stations inadequate to generalize local-scale UHI effect experienced by smaller geographical areas to the whole city due to surface heterogeneity, varying urban metabolism, and site-specific microclimatic factors. In response to this, a standard experimental protocol for a local-scale urban meteorological investigation (Oke, 2004) is strictly adhered to eliminate any form of biasness in the reported findings of this study. Thus, results of this study anticipated being representative for a local-scale UHI effect experienced within 500 m radius, from where the meteorological observatories located in each urban stations. Essentially, this study yields some vital findings that answered the existing knowledge gaps on the behaviour of UHI according to temporal variations in the local context. This study revealed highest seasonal UHII of 1.68 °C in PJ station in the month of June, a dry period associated with the southwest monsoon season. In fact, highest seasonal UHII (August: 1.29 °C) in SUB station is recorded during this monsoon season as well. PJ station evinced a distinct diurnal trend with the maximum nocturnal UHII of 1.71 °C at about 8 p.m. after sunset under favourable meteorological conditions. Besides this, UHI events occurred more frequently at nights in both PJ and SUB stations within the range 0–2 °C. Cooling at all urban sites starts around 2–3 p.m. with the highest rate of 0.73 °C/h and 0.96 °C/h in PJ and SEB stations respectively. Interestingly, UHI in both urban stations demonstrated a contrasting behaviour with relative humidity whereby a low positive association is detected ($r = 0.37, p \geq 0.05$) in PJ station and a strong negative correlation ($r = -0.79, p < 0.05$) is observed in SUB station respectively. On the other hand, wind speed exerts a moderately negative ($r = -0.44, p < 0.05$) correlation on UHII in PJ station and a very strong influence ($r = 0.83, p < 0.05$) on UHII in SUB station. Overall, this study provided a detailed description of the temporal variations of UHI in the selected well-developed urban areas in GKL, which highlights the influence of urbanization on the deterioration of thermal regime of a tropical city. At the same time, the acquired knowledge is expected to assist the urban planners and designers to undertake evidence-based adaptation and mitigation strategies efficiently to improve the urban thermal environment.

Despite providing an important contribution to tropical urban climate literacy, this study is subjected to several limitations. Firstly, the annual and inter-annual variability of canopy-level UHII that provide a logical representation of urbanization-induced detriment of local climate is not presented in this study due to data acquisition difficulties. Secondly, the three-dimensional urban morphology around meteorological observatories that may exert a notable influence on local UHII (Stewart & Oke, 2012) is not quantitatively discussed due to the lack of such data in this study. Thirdly, spatial variations of UHII is not evaluated due to limitations of in-situ measurements by standard meteorological observatories. Therefore, as a delimitation measure, future studies may employ some innovative approaches to the current methodology to produce comprehensive results of local UHI phenomenon. Integration of mobile weather trackers, drones and unmanned aerial vehicles with meteorological network’s observations produces a more holistic approach to cover an extended geographical area and vertical profile of UHI. Besides, incorporation of more explanatory variables of UHI from both meteorological and urban factors is a requisite to identify their pivotal association with UHI intensification in the tropical context. With such acquired knowledge of the UHI issue and related underlying mechanisms, urban planners, designers and decision makers can perform more evidence-based decision making to create, reform or rejuvenate climate-friendly sustainable cities for enhanced livability in future.

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