Alexandria Engineering Journal (2020) 59, 4475–4489

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Urban heat island in the modern tropical Kuala Lumpur: Comparative weight of the different parameters

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Received 10 August 2019; revised 1 April 2020; accepted 29 July 2020
Available online 8 August 2020

KEYWORDS

Relative humidity;
Tropical jungle;
Turbulence;
Urban heat island;
Wind

Abstract Over time, urban dwellers have become increasingly concerned with the thermal characteristics in their neighbourhood. Modern Asian cities with their environmental diversity have introduced complexity to urban heat island (UHI) predictions. This research aimed to discover the relative contribution of different environmental and anthropogenic parameters to the UHI intensity in Kuala Lumpur, Malaysia. Four days of temperature and wind data were collected from seven sites representing various land covers inside and outside the city. Besides, humidity and solar radiation time traces were gathered from selected sites. Delicate weather measuring equipment, such as ultrasonic anemometers, were used with existing equipment at Malaysia's Meteorological Department (Met. Department). Results showed a 6 °C UHI intensity at nighttime and a 4 °C urban cool island intensity at daytime. The effect of land cover on UHI dominates the effects of other factors, including wind speed and turbulence. This modern Asian urban configuration consisting of a few high-rise buildings surrounded by plant and water patches mitigates the UHI through evapotranspiration and shading.

1. Introduction

Greater Kuala Lumpur (KL) covers an area of 2793 km^2 and is the home of 7.2 million people. This number is nearly a quarter of Malaysia's population. Similar to other Asian cities, the economic growth in KL is accompanied by many high-

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Peer review under responsibility of Faculty of Engineering, Alexandria University.

https://doi.org/10.1016/j.aej.2020.07.053
1110-0168

ways, industrial facilities, complexes and high-rise buildings. For example, the city will have three of the world's highest skyscrapers, namely, the existing KL Twin Tower (451.9 m), the recently completed Signature or Tun Razak Exchange Tower (492 m) and the PNB 118 Tower (630 m), in the next 5 years [1]. The latter is still in construction at the time of writing. This urban sprawling implies replacing large green areas with building and paving materials. The urban surfaces are of low solar reflectance and thermal capacity, and the congested urban structures restrict the air flow through the city. Moreover, anthropogenic activities are typically accompanied by heat release and air pollutant emissions. In addition, the removal of jungles causes the loss of the evapotranspiration cooling effects provided by plants. These conditions cause an urban heat island (UHI) effect [2–4] which is defined as the rise in the temperature of the urban area in comparison with its rural surrounding [5,6]. This temperature rise starts from 2 °C and could increase to as high as a few degrees. The temperature rise in urban areas has negatively affected human health, the environment and the economy [7–13]. Therefore, urban sustainability implies controlling the UHI effects. Several mitigation techniques [14] such as (1) the use of reflective vegetated or permeable building and paving materials [15,16], (2) utilising vegetated spaces within urban areas [17], and (3) applying green or reflective roofs [18,19], have been proposed. The optimal practice is to utilise several techniques in combination with one another [20]. In KL, the second strategy can be the best choice since the land-surface is already green. What really matters is how to reach a reasonable compromise between green and built-up areas.

The UHI intensity depends on the balance between the sources of the UHI and the mitigating agents. The factors that are supposed to affect the strength of the UHI in KL can be summarised as follows.

1.1. Land-surface cover

Land cover is probably the most important factor that affects the UHI strength [3,10,14]. Green and water surfaces weaken the UHI effect, whereas built-up areas intensify it. Trees increase humidity through evapotranspiration and by shading ground surface. This results in inter-urban temperature differences that may be comparable to urban–rural differences [21]. Thus, the size of the green-covered area and its distribution within the city are crucial; several interspersed small green areas can mitigate the UHI more efficiently than one singular large park [22]. Masoudi et al. [23] and Masoudi and Tan [24] conducted spatial and temporal analyses of the relationships between urban composition (vegetation amount) and configuration (distribution), and land surface temperature in four Asian cities, namely, Singapore, Hong Kong, Kuala Lumpur and Jakarta. The authors found that despite undeniable effects of green surfaces on mitigating the UHI, the configuration of vegetated areas is slightly important unless they are evenly distributed in the city. The researchers concluded that the optimal UHI mitigation performance is obtained using large green patches of simple shapes, high connectivity, and minimal fragmentation. For instance, the green surfaces in Hong Kong are too small and patchy to influence the UHI effectively [25]. The effect of open water bodies on the UHI has not been quantified despite the broad literature that characterises the effect of vegetation [26]. The study held by Ramakreshnan et al. [27] indicates that the UHI correlation with meteorological parameters diverges between the urban and suburban areas of KL. Unfortunately, the study considered two sites only of the wide-spanning city.

The details of the land surface materials commonly used in Malaysian urban areas were collected from the various sources in the websites, specifications and typical drawings available at Malaysian Public Works Department.

1. Most buildings are made of concrete and bricks
2. Roof tiles are made of material having properties between that of concrete and bricks
3. Roads are made of asphalt

The physical properties of these materials can be found in Table C.4. Although new buildings are made of lighter materials such as the Lightweight Cellular Mortar (LCM) which density ranges between 600 and 900 kg/m^3, most building still use the conventional methods and materials i.e. bricks and concrete.

1.2. Urban configuration

The effect of urban configuration on the UHI represents a typical paradox because urban expansion either vertically (contiguity) [21,22,28–30] or horizontally (sprawling) [31] can contribute to city temperature rise. Urban contiguity indicates a high population density and a high building height-to-street-width ratio; either causes a shading effect in the morning [32] but additional heat release at night. Meanwhile, urban sprawling expands the land surface covered with impervious low-albedo materials and sets the city centre's temperature patterns far from its cool rural surrounding. According to Masoudi et al. [23], KL is classified as a sprawling city, however, the configuration of green surfaces do not contribute effectively to UHI mitigation.

1.3. Weather conditions

The UHI intensity is sensitive to background climate and weather conditions, namely, wind, humidity, cloud and secondary flows. Wind has an intuitive role in mitigating the UHI [33]. Despite the heating effect of solar radiation at daytime, the peak of the UHI, if it ever exists, occurs at nighttime [3,13,27,30,34,35]; the slow release of energy from urban surfaces combined with the calm wind condition provides a favourable situation for the UHI formation. At daytime, however, an urban area can be even cooler than its rural counterpart given the shading effect of buildings [25,26,36,37]. Furthermore, secondary wind flows, such as sea breeze and katabatic streams at sloped surfaces, alleviate the UHI intensity [30,38]. Humidity is another opponent of UHI such that it is less likely to form in humid climates [30,39,40]. Winter witnesses the UHI less frequently and less intensely than summer [37,41]. This condition largely depends on the wind and humidity characteristics of both seasons in each country [13,42]. In KL, the UHI events occur mainly at nighttime and its intensity ranges within 0–2 °C [27]. Kuala Lumpur, as a tropical city, encounters a hot and humid weather throughout the year. Nevertheless, the solar radiation is not constant since clouds cover the sky partly or totally in many days. The effect of clouds on UHI is not present in the literature, to be best knowledge of the authors.

1.4. Population and anthropogenic activities

Urban dwellers directly contribute to temperature rise in their neighborhoods through heat and pollutant release in transportation, air conditioning and other human activities. The UHI is likely to form in highly populated areas [26,30]. In some conditions, the effect of human activity type is equally important as water bodies [34]. A commercial district can be 2 °C cooler on weekends than on weekdays [10]. In addition, the UHI intensity in a metropolitan can be correlated to luxury or family income levels [3]. Tang et al. [43] examined the effect of land use on UHI. They arranged the different surfaces in accordance with their temperature as follows; (1) commercial/industrial, (2) residential, (3) barren, (4) forest, grassland, cropland, wetland and (5) water. These authors found that human activities and socio-economic patterns slightly impact UHI, unless they are accompanied by changes in land cover. Besides, despite the contiguity caused by the KL city centre high-rise buildings, they offer a shading effect. The weight of each factor in promoting or mitigating the UHI intensity is yet to be investigated.

The urban environment in modern Asian cities encompasses a diversity of land surfaces and anthropogenic activities. The current literature cannot identify absolutely the contribution of each parameter to the UHI effect. Our objective is to depict the factors that affect UHI in a modern tropical Asian city, such as KL, and assess the relative weight of each factor. The authors expected to determine a reliable characterisation of the UHI phenomenon in KL using temperature, wind speed, solar radiation and humidity sensors placed at seven sites inside and outside the city.

1.5. Overview of existing UHI study methods

A variety of techniques have been implemented to assess the effect of the aforementioned factors on UHI intensity. A summary of previous researches on factors influencing UHI intensity is listed in Table 1. A glance over the literature tells that the majority of the researches were conducted via satellite imagery. Despite its spatial power point, satellite imagery suffers a few drawbacks.

1. It cannot measure other meteorological parameters such as humidity and wind speed
2. Its resolution scales with tens of meters
3. The urban details are hard to identify
4. The precision of method is sensitive to the sky clearness; this makes measurements very difficult in the tropical cloudy KL
5. It cannot indicate the temporal variation of UHI

For these reasons, the authors found the traditional point measurement method more suitable for the target of the present research. The remainder of this article is organised as follows. Section 2 describes the observational sites and their instrumentations. Section 3 illustrates the results, and Section 4 discusses them. Finally, Section 5 lists the important conclusions.

2. Experimental setup

2.1. Sites

Seven datasets from different locations in KL were examined in the current research. Three datasets of them were captured by the current research team via new weather facility installations. These datasets were measured in (1) the heart of KL, that is, KL City Center (KLCC) Park, (2) the national stadium (Stadium Negara, S-N) and (3) the Independence Square (Dataran Merdeka, D-M). Setting the equipment in such crowded areas is very challenging. Approval from every owner or manager of measuring site was secured. KLCC Holdings, the manager of KLCC Park, could not provide an electrical source. Thus the only option was to utilise solar panel–battery system. However, the green canopy and skyscrapers make recharging of battery set very limited. The solar panel could only start charging the battery well by 8 am and continues until 6 pm before the sunset, that is a discount of one hour each at the start and end of sunshine potential of the days. In addition, the cloudy Malaysian sky reduces the solar radiation partly or nearly totally for several hours daily. Two solar panels of 220-W total capacity and two 12-V batteries arranged in parallel were utilised to maintain sufficient power. Fig. 1a and b illustrate the experimental set up near the children's playground and wading pool within the KLCC Park. These pictures also depict that the area is covered with high trees among the very high skyscrapers.

Stadium Negara (National Stadium) is the least congested site. The location lies on a relatively high hill. Some trees surround the stadium but the ground is mainly asphalt-covered. Minimal shading is provided by the stadium building. The stadium was not used within the study period (i.e. Feb. 2018–Aug. 2018). Thus, security was not much of a concern. Snap shots of S-N's surrounding are demonstrated in Fig. 2a and b. The measuring point within S-N is located approximately 100 m from the PNB 118 Tower discussed in Introduction. During the measurement, the PNB 118 tower was extensively constructed and was at approximately the 10th storey.

Dataran Merdeka is surrounded by low-to-medium-height buildings from all directions. The site is constantly active given daily visits and crowded weekends. Dataran Merdeka is on low-lying land which is nearly 150 m from the Klang River at one end. The instruments were installed beside the park security office of the city council (Dewan Bandaraya KL). This facility is used as the monitoring tower of the independence park. Snap shots for the anemometer at D-M and surroundings are exhibited in Fig. 3.

In addition to the data collected in the current project, four datasets gathered by other research centres were adopted in the analysis. These datasets are (1) measurements at the Parliament (Parl), (2) measurements at Petaling Jaya city (PJ), and (3) measurements at the Malaysia–Japan International Institute of Technology (MJIIT), Universiti Teknologi Malaysia (UTM), KL campus at an academic tower (68 m high) and (4) at the rooftop of a four-storey building (15 m) (U-68 and U-15, respectively). Each data set included at least temperature and wind speed and direction traces. Thus, our analysis

Table 1 Researches exploring the impact of the different factors on UHI.

Research	Study location(s)	Factor(s)	Method(s)	Meteorological parameter(s)	Study period
[37]	Łódź, Poland	Climate	3 meteorological stations (two at a time)	Wind speed	Four years (1934–1936 and 1992–1994)
		Diurnal cycle			
		Wind speed			
[16]	Athens, Greece	Mitigation strategies (Surface albedo)	Simulation	–	24 h
[10]	Portland, Oregon, USA	Land-surface cover	Vehicle traverses	–	6 days during the summer of 2006
		Human activity			
[3]	Phoenix metropolitan, Arizona, USA	Land-surface cover	Satellite imagery	–	Two day-night pairs of imagery from the summer (June) and the autumn (October) seasons.
		Human activity			
[44]	Nagoya, Japan	Mitigation strategies	Satellite imagery	–	Five images representing the four seasons
[19]	New York City	Land-surface cover	4 meteorological stations	–	December 2008 – February 2009, June 2009 – August 2009
			Simulation		
[26]	24 cities in Netherlands	Land-surface cover	27 meteorological stations	Wind speed	Eight years (2003–2010)
		Diurnal cycle		Solar radiation	
		Human activity (Population density)			
[21]	Hong Kong	Land-surface cover	Satellite imagery	–	Two images from two satellites (November and December)
		Spatial configuration of urban areas			
[34]	Turku, SW Finland	Land-surface cover	36 Temperature loggers	–	Six years (2002–2007)
		Climate			
[28]	274 cities in Europe	Spatial configuration of urban areas	Satellite imagery	–	June, July, and August 2001
[22]	The 50 most populous cities in the United States	Spatial configuration of urban areas	Grid of meteorological stations	–	Five years (2006–2010)
[25]	Hong Kong	Climate	58 logging sensors	Relative humidity	17 consecutive summer days
		Diurnal cycle		Solar radiation	17 consecutive winter days
		Land-surface cover		Rainfall	
		Human activity		Wind speed and direction	
[43]	Baltimore–DC metropolitan area	Land-surface cover	Satellite imagery	–	One image (22 August 2010)
		Human activity (Population density)			
[36]	Valencia, Spain	Climate	Two meteorological stations	–	Three consecutive hot summer days
[8]	Houston, Texas, USA	Mitigation strategies	Simulation	–	Hottest week of the Typical Meteorological Year
		Climate			
[23]	Singapore	Mitigation strategies (green space pattern)	Satellite imagery	–	Four images one per city
[24]	Singapore	Mitigation strategies (green	Satellite imagery	—	Five satellite images (1973 – 2015)

Table 1 (*continued*)

Research	Study location(s)	Factor(s)	Method(s)	Meteorological parameter(s)	Study period
		space pattern)			
[27]	Kuala Lumpur, Malaysia	Land-surface cover	Two meteorological stations	Relative humidity	One year (2016)
		Human activity		Wind speed and direction Atmospheric pressure Rainfall	

a Children's playground and wading pool side b Petronas Twin Towers background

Fig. 1 Ultrasonic anemometer and equipment erected at the KLCC Park.

included seven sets of data resembling scattered locations and different environments and heights within the Malaysian metropolitan. In summary, the conditions and GPS coordinates of the different sites are detailed in Table A.2. A map of all sites is represented in Fig. 4.

2.2. Instruments and equipment

Wind speed and air temperature were the basic parameters measured in all sites. In addition, other parameters such as relative humidity and solar radiation were measured to help interpret the temperature trends. Majority of data were captured at a frequency of one sample per minute (0.0167 Hz) and averaged over a 1-h interval, except the KLCC, S-N and D-M data which were collected at 1 Hz to allow the estimation of turbulence intensity. Table B.3 lists the instruments utilised at each site.

The three devices used by the current research team (KLCC, S-N and D-M) were calibrated before the experiment for the eastward velocity component (0–17 ms^{-1}) in the Pangkor low-speed wind tunnel at the Water Resources and Coastal Laboratory, the National University of Malaysia [45]. An error of less than 2% was achieved. The devices were also calibrated for temperature measurements by comparing their 48-h time series with each other under the same conditions. Accordingly, corrections of less than 1 °C were assigned to fit all readings. The measured sonic temperature can be designated as the virtual temperature with a negligible error [46,47]. The ordinary air temperatures T obtained by the other research centres (U-68, U-15, PJ and Parl) were converted to virtual temperatures, T_v using the following relation

$$T_v = T(1 + 0.32\frac{e}{p}), \quad (1)$$

where e is the water partial pressure in the atmosphere and p is the barometric pressure. The water partial pressure was calculated using the relative humidity and water vapour pressure at the measured temperature.

a Stadium Negara background   b City background

Fig. 2 Ultrasonic anemometer and equipment installed near S-N.

Fig. 3 Ultrasonic anemometer installed at D-M.

2.3. Climate

Malaysia's climate is categorized as equatorial, being hot and humid throughout the year. The study was held in the Malaysian dry season. The average temperature and relative humidity were 32 °C and 79%. The wind direction (Fig. 5) and hourly solar radiation (Fig. 6) are presented to help assess the climatic conditions during this research. Fig. 5 demonstrates the wind roses of the average wind speed, direction and frequency over the four selected days. The wind mainly blows from the south-east direction. Typical wind speeds in Malaysia are below 5 m/s [48–50]. The direction 68 m above ground (U-68, Fig. 5a) is shifted to the east direction, due to the Coriolis effect. The hourly solar radiation in KL is exhibited in Fig. 6. During the study period, sun rose at approximately at slightly before 7:00 am and set at 7:00 pm. Peak solar radiation occurred at 2:00 pm, except under cloudy conditions (Fig. 6c). The difference in land cover between the considered sites reflects on the hourly change in relative humidity (Fig. 7). The humidity at the Parl emulates that of PJ at daytime (7:00 am–3:00 pm) but increased at nighttime.

3. Results

This section discusses the temperature and wind data for the sites involved in this research.

3.1. Temperature

The temperature hourly variation at the seven sites for the studied days is illustrated in Fig. 8. The lowest temperature values were recorded at the green-surrounded Parl site. Thus, this site was used as a reference to assess the UHI intensity for the other sites. The UHI intensifies at the calm nighttime and diminishes at daytime. The UHI intensity at nighttime ranges between 3 °C and 6 °C, whereas that at daytime decreases to 1.5 °C and becomes an urban cool island (UCI, inverse UHI) in KLCC and S-N. The highest temperatures among all sites are recorded at PJ. Intuitively, the low temperature at U-68 is due to the high measurement altitude. The temperature at the neighbouring U-15 site reaches comparable values to that in PJ during morning hours, whereas the temperature drops to sub-normal values at nighttime. The temperature drop at the U-15 site at noon on 28 August was due to

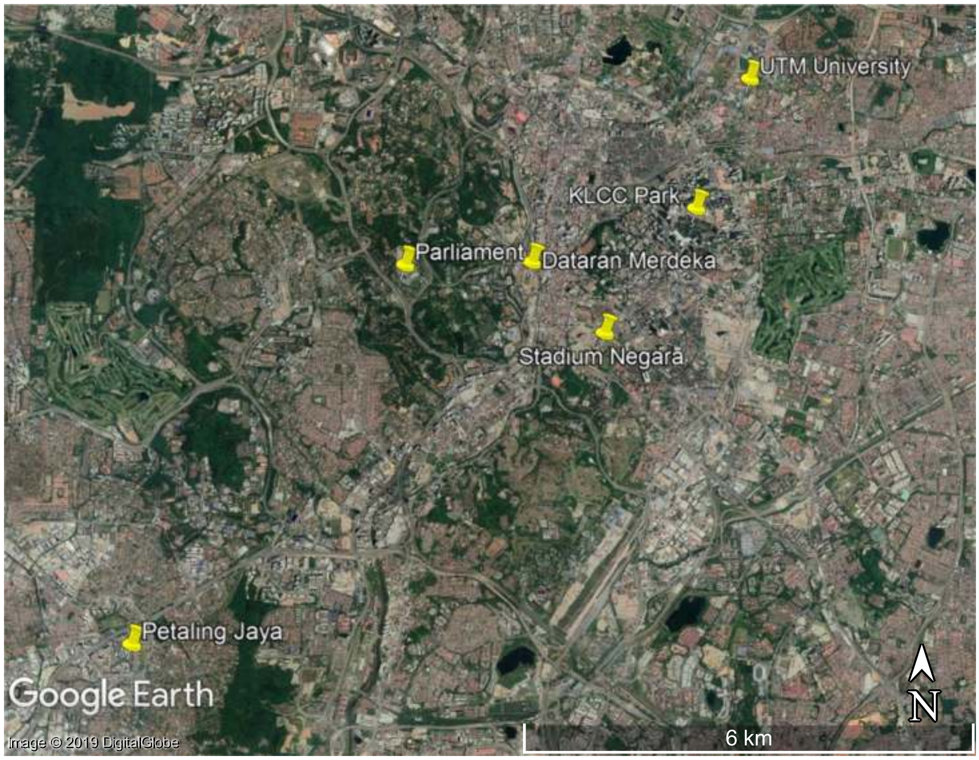


Fig. 4 Map of the data acquisition sites.

a cloudy weather. Amongst the three city centre sites, the KLCC exhibits the lowest UHI intensity over the 24-h period, followed by S-N and D-M. The D-M site is mainly hotter (1 °C) than S-N at daytime and cooler (0.5 °C) after midnight. These inter-urban temperature variations are due to the differences in land-surface cover between the city districts; while the ground of S-N is mainly covered with asphalt, the D-M is a large green park.

Plotting the UHI intensity in the seven sites (Fig. 9) better emphasises the results. A UHI intensity (such as Fig. 9) is constructed by subtracting the reference temperature (Parl). A UCI prevails at 6:00–9:00 am and can reach as high intensity as 4 °C (−4 °C UHI intensity). Areas surrounded partially or totally with greenery (KLCC, D-M, S-N and U-15) enjoy a stronger UCI. Except in PJ, the UHI starts to form at 12:00–3:00 pm. The mostly flat-land and sunny location of PJ suffers an early formation of the UHI such that the UCI is too short or almost absent. The U-68 station despite not enjoying shading effect, it is less affected by UHI at all day times. This is on account of the twofold effect of its high altitude which makes it far from land heating and subjected to strong winds. The troughs of UHI intensity at 3:00 pm on both 26 and 28 August is most probably due to cloud formation as can be inferred from solar radiation time series (Fig. 6b and c). The heat absorption during day hours reflects to the temperature trends after sunset. The peak UHI intensity takes place between 6:00 pm and 6:00 am and ranges in all sites most likely within 3–5 °C. The only exception is KLCC; even if the temperature recorded at daytime was equal to other sites, the UHI intensity is always lower. This may be owing to the water and dense green cover around the station as well as the shading effect of the Petronas Twin Towers which starts covering the station at afternoon. The shading effect in KLCC is pronounced in the lower UHI intensity peak and slower rise rate. The UHI intensity falls down rapidly after sunrise (after 6:00 am) due to temperature rise in the reference site.

The drastic difference in temperature patterns between Parl and PJ are explained as follows. The Parliament complex (Parl) is surrounded by greenery within a 2-km circle. This park contains a large lake (details in Table A.2). The Parliament complex only sees high traffic volumes from 7–9 am to 5–6 pm. There are little anthropogenic activities in the day. At night, after staff go home, there are not many activities around. Although the parliament building is made of bricks and concretes, much of the surrounding consists of typical garden with top soils and grasses. Together with the lake, the surrounding offer least thermal conductivity.

In contrast, the PJ site is the center of industry in the Greater Kuala Lumpur. The Free Industrial Zone (FIZ) which houses several multinational companies is located here. There are plenty of small and medium enterprise (SME) warehouses. There are few busy highways which include the Federal Highway, New Pantai Expressway and Sprint Expressway which surrounds this Met. Dept. weather facility. With exceptions of only a few days of the year, these expressways are congested except from midnight to 6 am. The location has very high population. i.e. approximately a papulation density of 4000/ km^2 in 2010 census by the Department of Statistics Malaysia, calculation by citypopulation.de. Petaling Jaya itself was granted a city status by the Malaysian Government in 2006. The increased UHI effects at PJ against that of Parl fit the descriptions by existing studies [18,20] where increased urbanisation is its primary cause. The second cause of UHI effect here is the thermal conductivities of surrounding materials and struc-

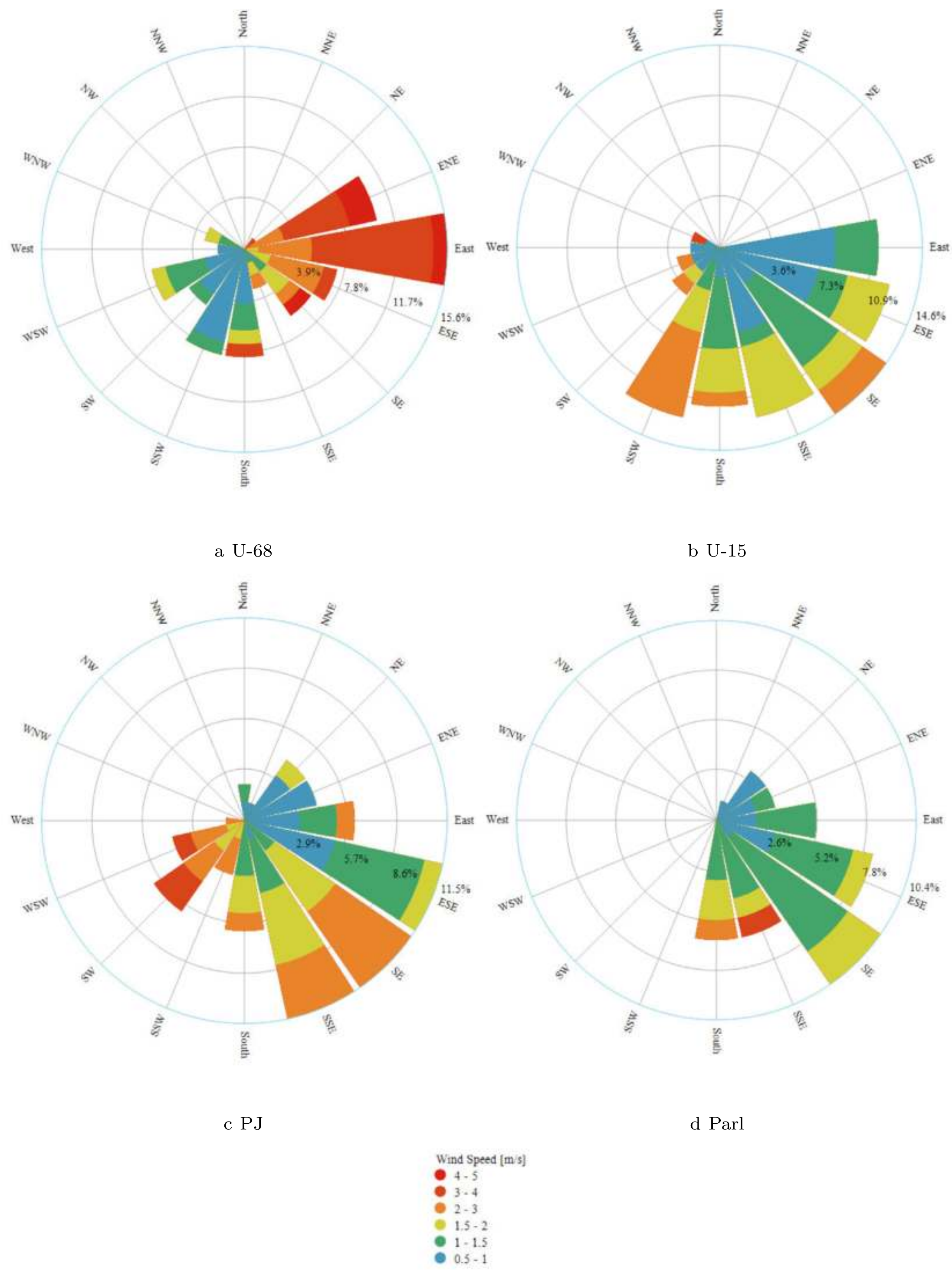
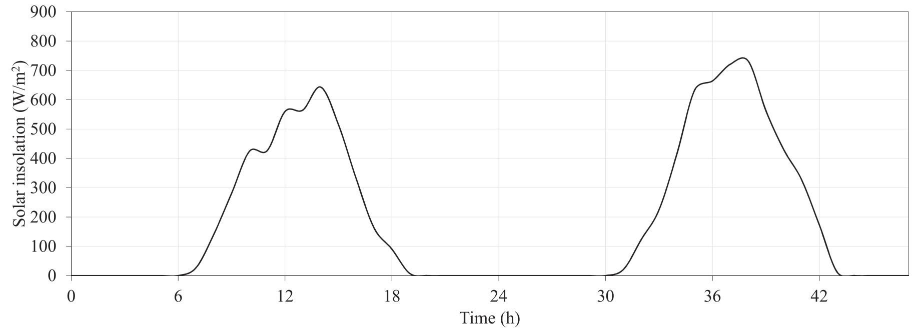


Fig. 5 Wind roses of the wind speed (m/s) and frequency (%) at each direction in the (a) U-68, (b) U-15, (c) PJ, and (d) Parl sites.

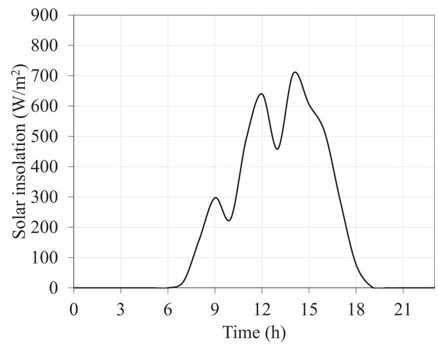
tures. Buildings which are made from brick and concrete has a thermal conductivity of 1.0 W/m K. Asphalt has a thermal conductivity of 1.5 W/m K depending on the density, fresh asphalt could absorbs approximately 95% of sunlight [20]. PJ has a lot more of buildings and expressways as compared with Parl. In addition, water and grasses with thermal conductivity of less than 1.0 W/m K, make up the significant part of parliament complex and are rare sights in PJ. The land materials properties can be found in Table C.4.

3.2. Wind

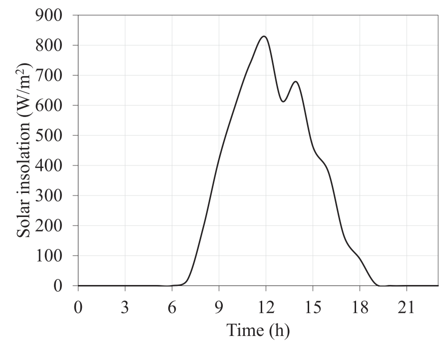
The change in wind speed with time at the different sites is illustrated in Fig. 10. As expected, the wind was strongest at



a 14–15 July

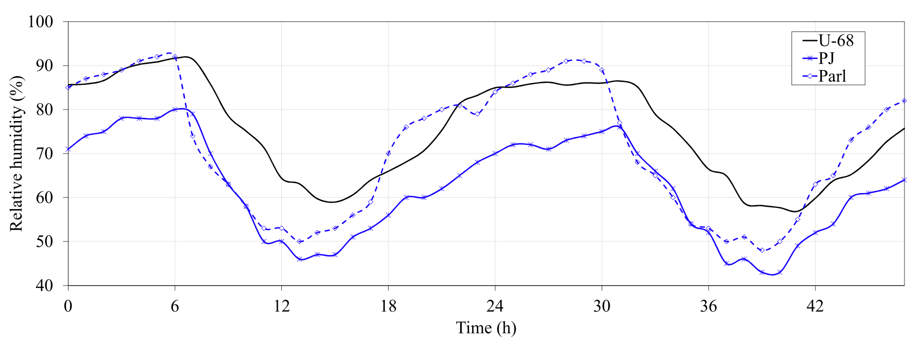


b 26 August

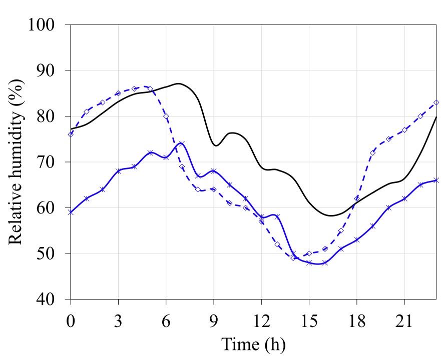


c 28 August

Fig. 6 Variation in solar radiation over day hours. (a) 14–15 July; (b) 26 August; (c) 28 August. Data were collected at the U-68 site.



a 14–15 July



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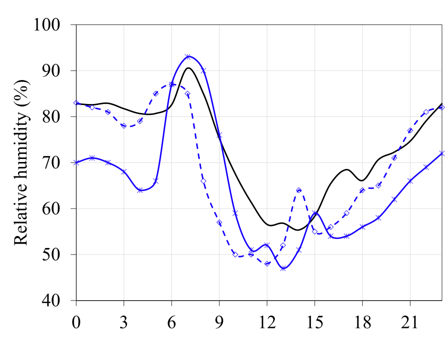


c 28 August

Fig. 7 Relative humidity variation over day hours. (a) 14–15 July; (b) 26 August; (c) 28 August.

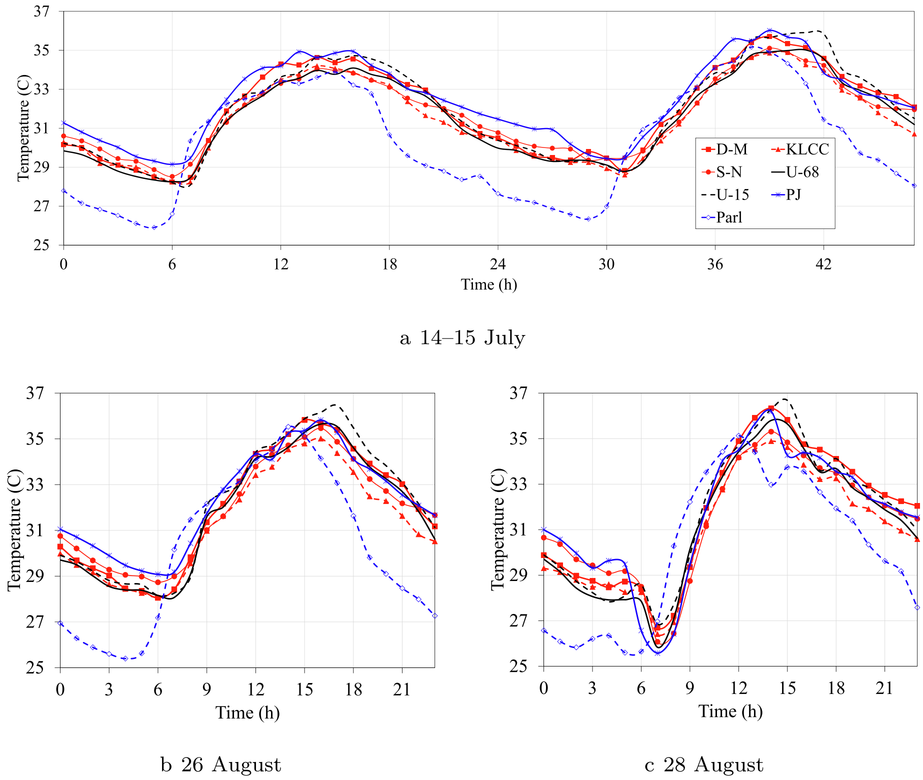


Fig. 8 Temperature variation over day hours. (a) 14–15 July; (b) 26 August; (c) 28 August.

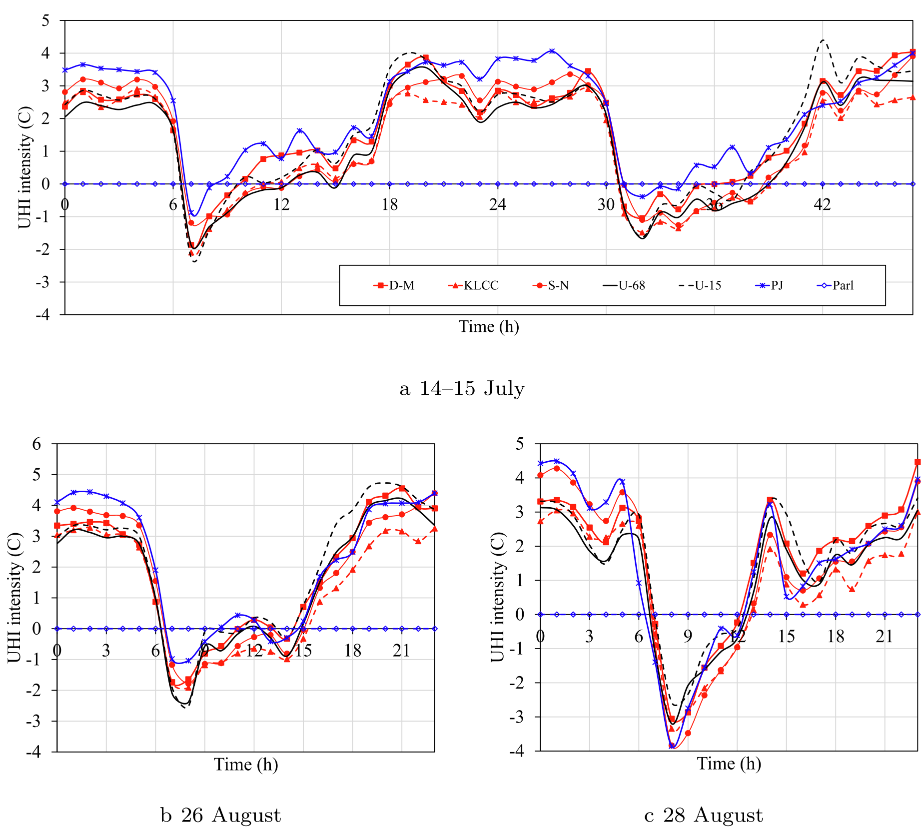
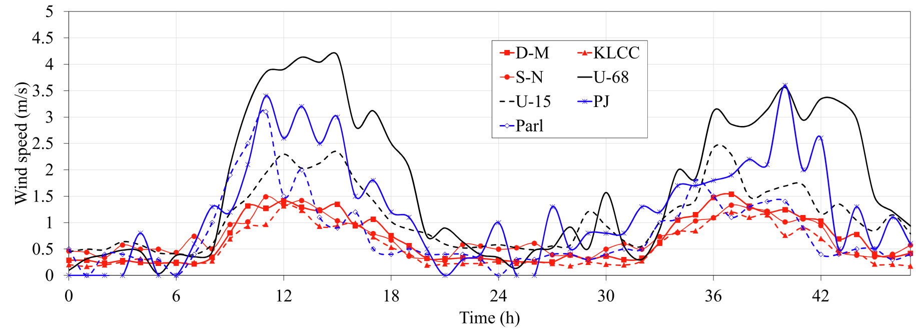
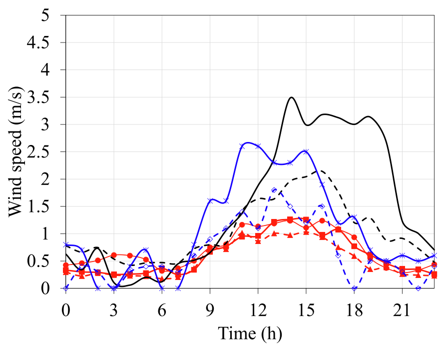


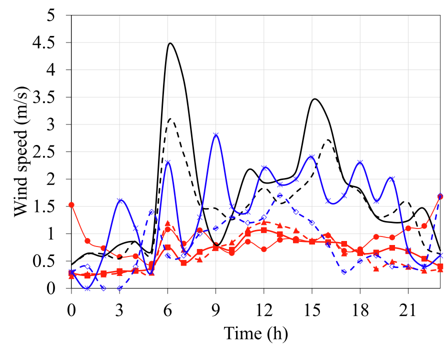
Fig. 9 UHI intensity variation over day hours. (a) 14–15 July; (b) 26 August; (c) 28 August. Data referenced to Par station.



a 14–15 July

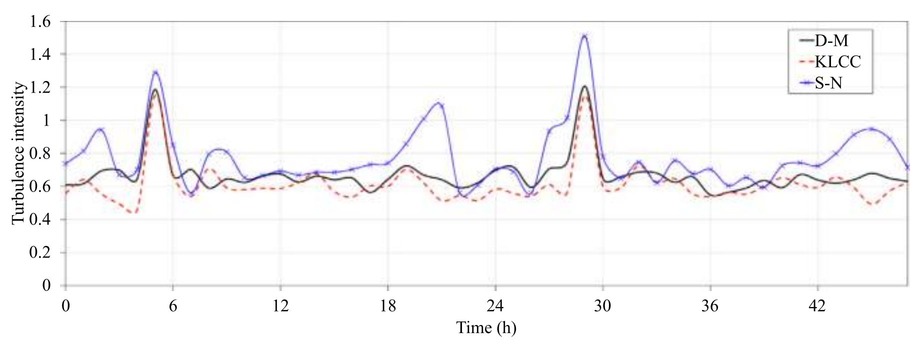


b 26 August

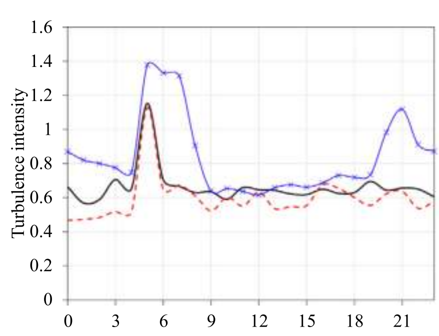


c 28 August

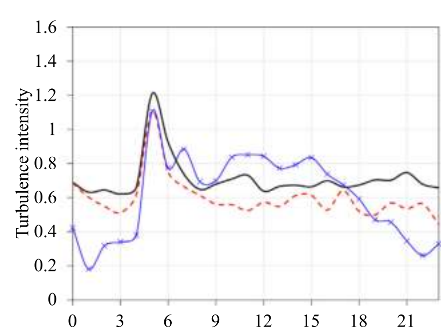
Fig. 10 Wind speed variation over day hours. (a) 14–15 July; (b) 26 August; (c) 28 August.



a 14–15 July



b 26 August



c 28 August

Fig. 11 Variation in turbulence intensity (σ_u/U) over day hours. (a) 14–15 July; (b) 26 August; (c) 28 August.

68 m above ground level (U-68). The wind speed in PJ displays high values which are sometimes comparable to the wind speeds at U-68. The weakest winds were recorded at KLCC followed by S-N and then D-M. Additionally, the turbulent activity of the wind blowing over the city centre is demonstrated in Fig. 11. A violent turbulent behaviour was recognised at S-N relative to D-M and KLCC, which experiences the calmest winds.

4. Discussion

We demonstrate the relative importance of the factors that affect the UHI in the city by analysing the temperature, wind, humidity and solar radiation data for the seven sites. Land cover remains the determinate parameter that affects atmospheric temperature [3,10,14,25,43]. The temperature is lowest within areas with large tracts of jungle (Parl) and highest in pure urban mid-rise building areas (PJ). In-between, penetrating the urban mass with green and water patches significantly relaxes the UHI from 6 °C to 3 °C. The high aspect-ratio building areas represented by the skyscrapers in KLCC can mitigate the UHI by providing a shading effect that decreases the solar insolation at daytime. This influence extends to the temperature at nighttime. This result leads to the conclusion that vertical expansion of cities can mitigate UHI provided that adequate green areas are located between buildings. The wind speed and turbulence slightly alters inter-urban temperature differences (e.g. the temperature is lowest at KLCC despite the weak wind activity at the area).

5. Conclusions

This research compared the weights of different factors of the UHI intensity in a modern Asian city, KL. Four continuous and discrete days of data from seven sites in different environmental conditions in the city were used in the analysis. The analysis included hourly variations in temperature, wind, humidity and solar radiation. The following conclusions are drawn from this research:

- The UHI in KL is most pronounced under calm night conditions. Inter-urban temperature differences (UHI intensity) range within 3–5 °C depending on land-surface cover.
- Kuala Lumpur witnesses an UCI during day hours because of the shading effect of high-rise buildings. The temperature in this UCI can go 4 degrees lower than the temperature in the rural surrounding.
- The major parameter in temperature variation within the city is land cover. Planted areas have been confirmed as the coolest within the city regardless of the other environmental conditions. The mostly brick and concrete building and asphalt roads and highway have higher thermal conductivity than grass on top soils. Materials with high thermal conductivity absorb more heat causing cooling to be delayed thus increases UHI effects.
- The modern Asian city design featured with high-rise buildings interspersed with green and water patches relaxes the UHI effect. The mix of shadows and green patches contributes to reducing the UHI intensity to half its value at night and generate a cool island at day.
- The shading effect of high-rise buildings overwhelms their wind restricting effect.
- Extended low- to medium-rise building areas displayed the worst thermal conditions among all the studied areas.
- Clouds contribute to relief UHI intensity; apparent depressions can be noticed in UHI intensity in coincidence with solar radiation declines. The effect of long-term persistent clouds in KL is not clear; it is recommended to conduct a similar study during the rainy monsoon season.

Finally, the authors expect the current research to be beneficial for civil planners and city counsel.

6. Patents

An intellectual property (IP) right has been recorded for the device called ‘Data Logger in Remote Areas’. The National University of Malaysia will undertake subsequent processes to file the IP at the national level.

Author contributions

Conceptualization, Z. Harun and E. Reda; approval, Z. Harun; methodology, Z. Harun and E. Reda; acquisition, A. Abdulrazzaq and A. Abbas; analysis, E. Reda and A. Abdulrazzaq; writing, review and editing, S. A. Zaki; supervision and project administration, Z. Harun; funding, Z. Harun; equipment - YOUNG Anemometer, Y. Yusup.

Funding

‘This research was funded by Ministry of Education Malaysia Grant No. FRGS/1/2016/TK03/UKM/02/1 and The National University of Malaysia Grants No. GUP-2018–102 and GUP-2020-015.’

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

These experiments involve the approval from city councils and premises. The authors are truly grateful to the following organisations:
1. Dewan Bandaraya Kuala Lumpur for allowing the use of their premise in Dataran Merdeka and the setting up of the experimental rigs;
2. PNB Merdeka Venture for providing permission to set up the experimental rig;
3. KLCC Holdings for allowing the use of their premise in the KLCC Park and the setting up of the experimental rig;
The authors would also sincerely appreciate the Department of Meteorological, Malaysia, under the Ministry of Energy, Science, Technology, Environment and Climate Change (MESTECC) for providing survey data and information on the meteorological station and the equipment used.

Appendix A. Description of the data measurement sites

See Table A.2.

Appendix B. Instruments used in each data set

See Table B.3.

Appendix C. Properties of typical land surface materials in Malaysian cities

See Table C.4.

Table C.4 Properties of typical land surface materials in Malaysian cities.

Material	Density (kg/m^3)	Specific heat capacity (J/kg K)	Thermal conductivity (W/m K)
Water	1000	4200	0.60
Typical garden with top soils and grasses	1060–1330	800 dry 1480 wet (mostly wet)	0.60–1.00
Concrete	2400	1000	1.13
Brick	2000	800	0.73
The top 150 mm of road materials which is asphalt premix	2300	900	1.0–2.0

Table A.2 Description of the data measurement sites.

No	Selected sites	GPS Coordinates	Description of land surface features and surrounding environment*	Data gathered by
1	KLCC Park (KLCC)	3°;9′;25.20″N 101°;42′;43.20″E	Heavily packed, numerous high buildings, in a park within the city with trees and a pool [51].	Present research team
2	Stadium Negara (S-N)	3°;08′;15.60″N 101°;42′;5.99″E	Lightly packed, no high buildings, no lake, a few trees, land partially covered with asphalt.	Present research team
3	Dataran Merdeka (D-M)	3°;12′;18.2″N 101°;41′;7.7″E	Moderately packed, 100 m away from roads, no trees, no lake, high buildings are located quite far away.	Present research team
4	UTM KL Campus – 68 m (U-68)	3°;10′;22.8″N 101°;43′;14.88″E	Moderately packed with low- and mid-rise buildings. High-rise buildings, mainly, MJIIT (53 m), Razak Tower (84 m) and Residensi Tower (94 m). Near roads, no lake, also surrounded by military and high-rise residential buildings. 68-m height.	MJIIT † [52]
5	UTM KL Campus – 15 m (U-15)	3°;10′;22.8″N 101°;43′;14.88″E	Ditto, 15-m height.	MJIIT †
6	Petaling Jaya (PJ)	3°;6';7.00"N 101°;38′;42.00″E	A 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 a few high-rise (> 9-storey: > 27-m) buildings, the sensor was 10 m high.	Department of Meteorology, MESTECC ‡ [27]
7	Parliament (Parl)	3°;8′;55.00″N 101°;40′;40.00″E	The complex comprises two parts, that is, a 3-storey main building and a 20-storey 77 m high tower, surrounded by greenery within a 2-km circle. This park contains a large lake.	Department of Meteorology, MESTECC ‡

‡ Ministry of Energy, Science, Technology, Environment and Climate Change.
† Malaysia–Japan International Institute of Technology.
* Unless mentioned otherwise, the sensor was placed at ≈1.5 m above ground level.

Table B.3 Instruments used in each data set.

No	Selected sites	Device(s)	Measured parameters	Accuracy
1–3	KLCC, S-N & D-M	81,000 ultrasonic anemometer, R.M. YOUNG	Wind speed & sonic temperature	± 0.05 m s^{-1} & ± 2 °C
4	UTM 68 m (U-68)	CS215-L, Campbell Scientific	Air temperate & relative humidity	± 0.4 °C & ± 2.0%
		03002–5 wind sentry, R.M. YOUNG	Wind speed & direction	± 0.5 m s^{-1} & ± 5°
		CS300 pyranometer, Campbell Scientific	Solar radiation	± 5%
		CS106, Vaisala	Barometric pressure	± 0.6 mb
5	UTM 15 m (U-15)	HD52.3D, DeltaOHM	Wind speed, direction & air temperature	± 0.2 m s^{-1}, ± 2° & ± 0.15 °C
6	Petaling Jaya (PJ)	WA151, Vaisala	Wind speed & direction	± 0.5 m s^{-1} & ± 3°
		JY 1000829, Jinyang Industrial	Air temperature	± 0.3 °C
		HMP115, Vaisala	Relative humidity	± 1.8 %
7	Parliament (Parl)	WXT530, Vaisala	Wind speed, direction, air temperate & relative humidity	± 0.3 m s^{-1}, ±3°, ± 0.3 °C & ± 3 %

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