Building Volume Effects on Ambient Temperature In The Kuala Lumpur City

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Abstract Buildings not only generate anthropogenic heat but also store and release heat energy which able to alter the urban microclimate. The heat released in the atmosphere contributes to the rise in ambient temperature, causing thermal discomfort towards urban dwellers, especially in hot and humid climate regions such as the Kuala Lumpur City. Due to urbanization, many buildings were erected leading to higher heat absorption within this city. This study aims to investigate the contribution of building volume on the ambient temperature of the Kuala Lumpur City. Using the Weather Research and Forecasting (WRF) simulation model, the ambient temperature of the city was regenerated within an intermonsoon phase (April) in the year of 2018. This period was chosen to reduce the synoptic forcing. Building footprints stored in GIS-based vector dataset was used to estimate building volumes within the city. Spearman correlation test and Kruskall Wallis test has revealed that the building volumes within the city has significantly affected the ambient temperature causing thermal discomfort towards the urban dwellers especially during the day. Spatial examination revealed that higher building volume contribute to warmer environment within the city centre. Thus, optimization of the building volume should be seriously considered especially during urban planning decision making.

Keywords: building volume, ambient temperature, urban microclimate, WRF-ARW, GIS

1. Introduction
The urban climate condition is reported to depend on the urban morphology. Urban morphology refers to the arrangements of urban structures (geometry) and the materials that make up the urban features. From previous studies, it has been found that the urban morphology of different cities will have different impacts on their urban climate. Several studies indicate that the variability of urban characteristics results in different impacts on the urban climatic condition [1].

The factors that determine the extent to which an urban climate differs from the climate of the surrounding area are formed by the characteristics of the built environment and the activities that take
place there. There has been a long debate on the characteristics of the urban morphology. Many studies suggested that it is important to closely represent the actual situations of the urban climate condition in the urban climatic map.

Above all, the compactness of a city needs to be examined. Most of the previous studies agree that compact developments (built-up areas) with many tall buildings will increase the temperature [2] [3] [4]. The composition and configuration of urban morphology feature significantly affect the magnitude of the daytime near-surface air temperature and surface temperature [5]. The microclimate conditions not only showed a high level of variation between different urban fabric types but also within individual quadrants across relatively small distances [6]. A study conducted in Phoenix, Arizona, has concluded that compact development with high concentrations of buildings, structures, and impervious surfaces increases radiative heating and intensifies UHI effects, but the study also indicates that tall buildings play a significant role in reducing urban heat [7]. Therefore, detailed analyses regarding urban compactness should be conducted.

Building volume and density play an important role in modifying the urban climate condition within an urban area. Buildings are the artificial human-made structures that encompass residential areas, offices, business areas and industrial areas which constructed for the benefits of human wellbeing. Some of the buildings are unique in shapes and designs such as skyscrapers and landmarks whereas most buildings will have a common square and rectangular shapes especially within business areas, residential areas and industrial areas.

Residential areas are often found in flat plains with little variation in elevation. Offices and business areas are usually located together in a region where human daily activities are high during the day. Industrial areas on the other hand situated a little further from the other areas as they usually produce harmful gases and disturbing noise that will not be easy for residents and workforces. These areas are usually found in urban areas and often accumulated at the centre of the urban region making the building density to be high. If the building density is high, the heat release will be slow down by limited open spaces making the temperature to be elevated especially at night. This is also associated with the limited sky view factor effects on heat release rate.

Additionally, building is the common parameter to estimate the city volume, density and surface roughness. Different demands and cultures lead to different amount of building volume and density in the country. The density will then describe different surface roughness. For example, in Tokyo, Japan, the building volume and density are high due to compact buildings; whereas, the building volume and density in Istanbul is less dense from Tokyo due to sparse buildings [8].

Building volume and density always impact the behaviour of the prevailing winds within urban areas. High density cities such as Beijing and Hong Kong prevent the wind to flow freely in the urban areas. The wind will break and weaken by the packed buildings and results in wind dispersion. Wind is one of the important medium to transfer heat and pollution away from the city. High density cities are unable to allow the heat and pollution to be transferred by the wind. This leads to severe urban heating and polluting the air within cities. Building density usually associated with surface roughness. The higher the urban density will result in higher surface roughness. High surface roughness tends to weaken the wind velocity that blows within urban regions. Residential areas are usually packed, and identical-shape houses can be found within the areas and not contributes to the surface roughness. Though, since the impervious coverage is high, this area tends to have higher temperature due to latent heat stored within the residential buildings [9].

Based on the reviews made, it is crucial to investigate the impacts of building volumes towards the ambient temperature in this city. The findings of this study can be used to assist the urban planners to make informed decisions during city planning processes. Hence, the city climate can be preserved which in line with the new urban agendas introduced by the United Nation (UN).
2. Methods
The present study employed the WRF-ARW simulation to reproduce the air surface temperature for the specific date chosen. The simulation was spun up for two days (48 hours) to reconstruct the original weather on the selected date. The lateral boundary condition was fed every six hours by utilizing the NCEP FNL Operational Global Tropospheric Analysis data. The data was supplied by Global Data Assimilation System (GDAS) with a resolution of 0.25° × 0.25°.

2.1 Physics Scheme Configuration
The physics schemes chosen were a set of well-tried options conducted by [10]. This option has successfully simulated the diurnal air surface temperature and wind components of the Kuala Lumpur City with the accuracy of over 90% in agreements with the ground observations. Using the same physics schemes as the previous study by [10], this study has simulated the diurnal air surface temperature and wind components of the study area. Table 1 shows the physics schemes employed during the study.

| Physics Option          | Scheme                        |
|-------------------------|-------------------------------|
| Microphysics            | WRF Single-Moment 6-class scheme |
| Longwave Radiation      | RRTM scheme                   |
| Shortwave Radiation     | Dudhia scheme                 |
| Surface Layer           | MM5 similarity                |
| Land Surface            | Noah Land Surface Model       |
| Planetary Boundary Layer| Yonsei University scheme      |
| Cumulus Parameterization| Kain-Fritsch scheme           |

2.2 Nested-Domain Setup
In the study, the diurnal air surface temperature and wind components were simulated using four nested domains with the grid size of 37.5km (40 × 40), 12.5km (88 × 88), 2.5km (201 × 201) and 0.5km (151 × 151). The dimensions in the parentheses are the grid dimensions designed in the easting and northing direction. Based on Figure 1, the centre of all four domains were focused on the location of the Kuala Lumpur City to provide relaxation zone to the domains, intended to reduce the errors by employing the LBC [11]. The largest domain (D01) covered part of Southeast Asia region and the smallest domain (D04) was designed to focus on the Klang Valley region where the Kuala Lumpur City is located.
The four domains designed for the simulation are shown in Figure 1. The parent domain covers several countries such as Malaysia, Thailand, Myanmar, Indonesia, Singapore and Brunei. The second and third domains were focused on the Peninsular of Malaysia with different area coverage as well as pixel sizes. The smallest domain was designed to cover the entire Kuala Lumpur City with the pixel size of 500m x 500m to coincide with other datasets prepared.

2.3 Air Surface Temperature Extraction
The air surface temperature produced by WRF-ARW was stored in NetCDF data format. This format was converted into GIS-based raster data layer to ease the data processing and analysis. Using “Create NetCDF raster layer” tool developed in the ArcGIS software, hourly air surface temperature data layers were extracted. These layers were stored as a single raster layer for each hour.

The simulated hourly air surface temperature layers were then combined to produce the mean air surface temperature layer. “Raster Calculator” tool was used to calculate the average of the air surface temperature layers. Since the simulated air surface temperature layers covered a large area, the masking technique was used to select the air surface temperature within the study area only.

2.4 Building Volume Estimation
The estimation of the building volume within the city was made using Equation 1. The building height information in building footprint data layer was used as the third dimension to estimate the building volume. The building volume is converted into percentage using the highest building (over 500m x 500m area) as the highest volume. The building volume layer was converted into raster data layer. The layer was then resampled into 500m x 500m pixel resolution.

\[
Building \, Volume(\%) = \frac{\sum (\text{height} \times \text{footprint})}{\sum (\text{highest height} \times 500m \times 500m)} \times 100
\]  

(1)
3. Results
Table 2 describes the hourly minimum, maximum and mean values of the air surface temperature for the entire Kuala Lumpur City. The daily air surface temperature of the city ranged between 22.3˚C to 34.8˚C. The lowest air surface temperature was documented at 7am with the value of 22.3˚C. The highest air surface temperature was at 3pm with the value of 34.8˚C. The lowest mean air surface temperature of the city was at 7am with the value of 25.9˚C whereas the highest mean temperature was at 4pm with the value of 33.7˚C.

Table 2. Hourly Minimum, Maximum and Mean Value of the Air Surface Temperature

| Time  | Minimum | Maximum | Mean  |
|-------|---------|---------|-------|
| 0100  | 23.8    | 28.2    | 27.2  |
| 0200  | 23.4    | 28.1    | 26.8  |
| 0300  | 23.2    | 27.7    | 26.5  |
| 0400  | 23.6    | 27.5    | 26.4  |
| 0500  | 22.7    | 27.3    | 26.2  |
| 0600  | 23.1    | 27.1    | 26.1  |
| 0700  | 22.3    | 26.9    | 25.9  |
| 0800  | 22.6    | 27.2    | 26.0  |
| 0900  | 24.9    | 28.5    | 27.3  |
| 1000  | 26.0    | 29.4    | 28.6  |
| 1100  | 27.5    | 31.1    | 30.1  |
| 1200  | 28.5    | 32.0    | 31.2  |
| 1300  | 29.7    | 33.3    | 32.3  |
| 1400  | 30.1    | 34.3    | 33.1  |
| 1500  | 30.6    | 34.8    | 33.4  |
| 1600  | 30.6    | 34.7    | 33.7  |
| 1700  | 30.0    | 34.7    | 33.5  |
| 1800  | 28.7    | 34.3    | 32.3  |
| 1900  | 26.4    | 32.5    | 30.9  |
| 2000  | 26.1    | 31.4    | 29.7  |
| 2100  | 26.1    | 30.6    | 29.1  |
| 2200  | 24.5    | 29.7    | 28.3  |
| 2300  | 24.1    | 29.1    | 27.9  |
| 2400  | 23.8    | 28.7    | 27.5  |

Even though the hottest period of the city was documented at 3pm as denoted by the minimum temperature of 30.6˚C and the maximum temperature of 34.8˚C, higher mean temperatures were documented at 4pm and 5pm with the value of 33.7˚C and 33.5˚C respectively. Therefore, the finding suggests that the hottest period of the study area is between 3pm to 5pm. The difference between the lowest (coolest period) and highest (hottest period) air surface temperature value was found to be quite
large with a difference of approximately 12.5°C. This is due to the variation of the urban morphology of the Kuala Lumpur City which consists of various urban features, material, geometry, structures and other physical components which contributes to wide range of temperature changes. Previous studies have also confirmed that spatial heterogeneity plays an important role in altering the air surface temperature within an urban area [12].

The diurnal pattern of the minimum, maximum and mean of the air surface temperature values is shown in Figure 2. As can be seen, the diurnal pattern of the air surface temperature of the Kuala Lumpur City consists of increasing and decreasing patterns. The pattern can be divided into three stages namely Stage 1, Stage 2 and Stage 3. During Stage 1, the air surface temperature of the city was slowly decreasing from the midnight until dawn and reached its bottom line at 7am. Then, from 8am the air surface temperature rapidly increased and reached its highest point at 4pm. In Stage 3 the air surface temperature rapidly decreasing from 5pm until midnight. This diurnal pattern is strongly influenced by the solar radiation. Since the city is located near to the Equator, the amount of solar radiation received is approximately 12 hours a day. Based on the graph, the study found that the city receives the solar radiation starting from 7am in the morning until 7pm in the evening. Stage 2 depicts the existence of solar radiation as denoted by the increase in the air surface temperature. In contrast, Stage 1 depicts the absence of the solar radiation as denoted by the decrease of the air surface temperature. Even though Stage 3 has shown decreasing pattern, the solar radiation is still present but weaker than in Stage 2.

![Figure 2. Air Surface Temperature Diurnal Pattern](image)

This study also examined the spatial distribution of the air surface temperature within the Kuala Lumpur City. Figure 3 shows 24-hour distribution of the air surface temperature of the study area. Based on the results, the study has identified that the Kuala Lumpur City, as delineated by black outline, is a heat island as exhibited by the concentration of higher temperatures within the city as compared to its surroundings. Hourly the air surface temperature of the city remained higher than its surrounding which indicates that the city is a heat island throughout the day. During the day, the accumulation of heat within the city is worsened and dispersed towards the western regions of Selangor state with very high concentration of heat. This may due to the high numbers of developments in the western region of Selangor state that make up the conurbation of the Greater Kuala Lumpur and Klang Valley. At night, it can be clearly seen that the western regions of Selangor state cool down more than the Kuala Lumpur City at night.
Figure 3. Hourly Air Surface Temperature Distribution of Kuala Lumpur and its Surrounding
Figure 4 presents the daily mean air surface temperature distribution of the Kuala Lumpur City. It is found that 68.9% of the city areas have the air surface temperature ranging from 29°C to 30°C while lower temperatures only cover 28.5% (refer to Table 3). The northeastern part of the city was found to be cooler than the other region. This area is surrounded by the Titiwangsa Range which consists of forest and located on high ground. The western part of the city experienced serious warming except in some areas in north-western region. This is because this region is packed with man-made features and urban developments that contribute to the heating process. The green cover within this region is also degraded rapidly, thus reducing the cooling agent within the region. Taking into account that this region located in lower terrain, the wind environment is also at a disadvantage.

Based on Figure 4 and Table 4, the lowest air surface temperature was identified in hilly area of Bukit Tabur. Other than Bukit Tabur, several areas such as Bukit Kiara, Bukit Tunku, Bukit Besi and Bukit Dinding were also identified to have lower air surface temperature distribution. Similar characteristics of these areas established the initial hypothesis; the areas which are located in higher terrain, have less developments and rich in green cover resulting in lower air surface temperature distribution. The highest air surface temperature was identified in Sri Petaling which is located in south-western region. Higher air surface temperature was also found in other areas such as Kepong, Danau Kota, Bukit Bintang, Chow Kit, Kampung Baru and Segambut. Urban areas which are packed with manmade features, have less green cover and located in lower terrain can cause the air surface temperature to increase.

In relation to the results and initial hypothesis, preliminary inferences were made; the regions with high green cover are able to keep the air surface temperature low, the regions which are more developed and compacted with built-up areas will increase the air surface temperature and higher regions have lower air surface temperature distribution as compared to the lower regions. These preliminary inferences established as the basis of this study and in line with the previous studies findings [2] [10][13] [14] [15].
Table 3. Air Surface Temperature Area Coverage

| Temperature Range (°C) | Area Coverage (%) |
|------------------------|-------------------|
| 26.0 – 26.5            | 0.3               |
| 26.5 – 27.0            | 0.2               |
| 27.0 – 27.5            | 0.9               |
| 27.5 – 28.0            | 8.4               |
| 28.0 – 28.5            | 12                |
| 28.5 – 29.0            | 6.7               |
| 29.0 – 29.5            | 29.6              |
| 29.5 – 30.0            | 39.3              |
| 30.0 – 30.5            | 2.7               |

Figure 4. Air Surface Temperature Distribution
Table 4. Air Surface Temperature

| ID | Name            | Air Surface Temperature |
|----|----------------|------------------------|
| 1  | Mont Kiara      | 27.1                   |
| 2  | Sungai Penchala| 28.3                   |
| 3  | Kepong          | 29.8                   |
| 4  | Bukit Tunku     | 28.1                   |
| 5  | Segambut        | 29.7                   |
| 6  | Bukit Damansara | 29.3                   |
| 7  | Petaling Jaya  | 30.2                   |
| 8  | Sri Petaling    | 29.9                   |
| 9  | Bukit Jalil     | 28.6                   |
| 10 | Sungai Besi    | 30.0                   |
| 11 | Bangsar South   | 29.9                   |
| 12 | Bukit Petaling  | 29.6                   |
| 13 | Salak Selatan  | 28.6                   |
| 14 | Pudu            | 29.4                   |
| 15 | Kampung Baru   | 28.5                   |
| 16 | Bukit Bintang  | 29.3                   |
| 17 | Chow Kit        | 29.4                   |
| 18 | KL Central      | 29.5                   |
| 19 | Bukit Besi     | 28.7                   |
| 20 | Cheras Utama   | 28.8                   |
| 21 | Kampung Pandan  | 28.3                   |
| 22 | Maluri          | 28.4                   |
| 23 | Pandan Perdana  | 28.4                   |
| 24 | Wangsa Maju     | 27.6                   |
| 25 | Setapak         | 27.9                   |
| 26 | Danau Kota      | 27.8                   |
| 27 | Kampung Datuk Keramat | 28.2     |
| 28 | Bukit Tabur     | 26.4                   |
| 29 | Desa Melawati   | 27.8                   |
| 30 | Gombak          | 28.2                   |
| 31 | Pantai Dalam    | 30.0                   |
| 32 | Bukit Gasing    | 27.8                   |
| 33 | Jinjang         | 29.6                   |
| 34 | Sentul          | 29.3                   |

The building volume parameter was derived from 3-dimension (3D) building where the tallest building was used as the maximum ceiling of the third dimension (height) within an area of 500m x 500m. Figure 5 shows the distribution of the building volume in the Kuala Lumpur City. The highest building volume is 100% which indicates that the air space of that area is filled with buildings whereas the lowest building volume is 0% which indicates the absence of building within the area.
The spatial distribution of the building volume map (refer to Figure 5) revealed that most of the regions in the Kuala Lumpur City has low building volume. This indicates that the city’s air space is free from tall buildings which can obstruct the air ventilation within the city. Nevertheless, there are some areas which have high building volumes such as the KL Central, Pudu, Bukit Bintang, Chow Kit and Bangsar South. As shown in Table 5, 95.2% of the city were dominated by lower building volume ranging from 0-20%. The table also shows that higher building volumes only cover 0.5% of the entire study area.

**Table 5. Building Volume Area Coverage**

| Volume (%) | Area Coverage (%) |
|------------|-------------------|
| 0-10       | 80.8              |
| 10-20      | 14.4              |
| 20-30      | 2.7               |
| 30-40      | 1.3               |
| 40-50      | 0.4               |
The building percentages of other important areas are shown in Table 6. The highvolume areas are mainly located in the central region of the Kuala Lumpur City where many business activities are held. The study has also found that Mont Kiara has high building volume even though the built-up coverage was found to be lesser than other areas in the city due to tall buildings. Therefore, these areas are expected to have higher thermal variation as compared to the outskirts.

| Percentage Range | Building Percentage |
|------------------|---------------------|
| 50-60            | 0.1                 |
| 60-70            | 0.1                 |
| 70-80            | 0.1                 |
| 80-90            | 0.1                 |
| 90-100           | 0.1                 |
Another urban parameter tested which significantly affect the variation of the air surface temperature was the building volume. The correlation test conducted has shown that the building volume correlated with the variation of the air surface temperature. In the previous study by [4], building volume is blamed to have the most significant impacts towards the air surface temperature within tropical environment.

Table 6. Building Volume Percentage

| ID | Name             | Building Volume Percentage |
|----|------------------|---------------------------|
| 1  | Mont Kiara       | 0.0                       |
| 2  | Sungai Penchala | 1.0                       |
| 3  | Kepong           | 8.2                       |
| 4  | Bukit Tunku      | 4.4                       |
| 5  | Segambut         | 4.7                       |
| 6  | Bukit Damansara  | 4.3                       |
| 7  | Petaling Jaya   | 5.4                       |
| 8  | Sri Petaling     | 7.7                       |
| 9  | Bukit Jalil      | 5.0                       |
| 10 | Sungai Besi     | 11.0                      |
| 11 | Bangsar South    | 10.7                      |
| 12 | Bukit Petaling  | 0.0                       |
| 13 | Salak Selatan   | 3.7                       |
| 14 | Pudu             | 10.2                      |
| 15 | Kampung Baru    | 3.6                       |
| 16 | Bukit Bintang   | 13.4                      |
| 17 | Chow Kit        | 8.1                       |
| 18 | KL Central       | 12.6                      |
| 19 | Bukit Besi      | 0.0                       |
| 20 | Cheras Utama    | 6.2                       |
| 21 | Kampung Pandan  | 5.3                       |
| 22 | Maluri           | 12.1                      |
| 23 | Pandan Perdana  | 2.0                       |
| 24 | Wangsa Maju     | 4.7                       |
| 25 | Setapak          | 22.1                      |
| 26 | Danau Kota      | 30.0                      |
| 27 | Kampung Datuk Keramat | 8.4     |
| 28 | Bukit Tabur     | 0.0                       |
| 29 | Desa Melawati   | 4.4                       |
| 30 | Gombak           | 0.0                       |
| 31 | Pantai Dalam    | 0.1                       |
| 32 | Bukit Gasing    | 0.0                       |
| 33 | Jinjiang         | 9.2                       |
| 34 | Sentul           | 6.2                       |
Furthermore, the properties of the urban materials and sky view factor obstructions lead to slow rate of heat release as well as wind flows within the city [9], [16]. However, this study revealed that the effect of building volume on the air temperature variation within the city was less significant. This might be due to less compact areas in the Kuala Lumpur City as compared to Hong Kong. High volume buildings in the Kuala Lumpur City are usually fragmented with the green covers [2] making this urban parameter to be less dominant than the others based on the p-value obtained from significance test. However, building volume was still listed as one of the significant urban parameters that can explain the thermal variations within the Kuala Lumpur City.

The relationship between the building volume and the air surface temperature is shown in Equation 2. An increment of 1% of building volume will increase the air surface temperature by 0.017°C. It can be concluded that 58% increment of building volume within the city will increase the air surface temperature by approximately 1°C.

\[ y = 29.959 - 0.017x \]

where, \( y \) - air surface temperature
\( x \) - building volume percentage

4. Conclusion
This study has identified that building volume contribute to the rise in ambient temperature of the Kuala Lumpur city. Based on the Spearman’s rho result, it can be said that the effects of the building volume on ambient temperature is quite strong. Further analysis revealed that the impacts of building volume towards ambient temperature was significant. Thus, building density should be included as one of the aspects to be considered during urban planning decision making.

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