The effects of green areas on air surface temperature of the Kuala Lumpur city using WRF-ARW modelling and Remote Sensing technique

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Abstract. Matured trees contain high concentration of chlorophyll that encourages the process of photosynthesis. This process produces oxygen as a by-product and releases it into the atmosphere and helps in lowering the ambient temperature. This study attempts to analyse the effect of green area on air surface temperature of the Kuala Lumpur city. The air surface temperatures of two different dates which are, in March 2006 and March 2016 were simulated using the Weather Research and Forecasting (WRF) model. The green area in the city was extracted using the Normalized Difference Vegetation Index (NDVI) from two Landsat satellite images. The relationship between the air surface temperature and the green area were analysed using linear regression models. From the study, it was found that, the green area was significantly affecting the distribution of air temperature within the city. A strong negative correlation was identified through this study which indicated that higher NDVI values tend to have lower air surface temperature distribution within the focus study area. It was also found that, different urban setting in mixed built-up and vegetated areas resulted in different distributions of air surface temperature. Future studies should focus on analysing the air surface temperature within the area of mixed built-up and vegetated area.

1. Introduction

The benefits and advantages of urbanization are undeniable. However, excessive urbanization can become uncontrollable and resulted in environment degradation [1]. Rapid conversion of vegetated areas into urban areas increased the air surface temperature and modified the urban climate condition which leads to the formation of Urban Heat Island phenomenon [2-4]. Therefore, consideration on urban climate in urban planning is suggested by many previous studies [1, 5-8]. Many earlier studies have indicated that green vegetation has the capability to regulate the high temperature within urban areas [9-11]. Therefore, there is a need to study the response of green area towards urban cooling as one of the mitigation strategy in urban planning. Previous studies demonstrated that the Weather Research and Forecasting (WRF) model was able to simulate the air surface temperature well within tropical cities[12, 13]. Remote sensing and Geographical Information System (GIS) techniques are often employed by previous studies for spatial-based analysis regarding climates [1, 4, 14, 15].
Therefore, this study attempts to identify the relationship between the air surface temperature and the green vegetation by employing WRF modelling and remote sensing as well as GIS technique.

2. Study Area
This study focuses on the Kuala Lumpur city. This city has a tropical climate since it is located in lower latitude region (03°N, 101°E). The selection of this city as the study area is due to the rapid urbanization that has taken place in the last few decades. The variability of urban morphology and urban settings also made this city is suitable for this study. Kuala Lumpur is the capital of Malaysia and is the densest city in the country. Located in the west coast part of Peninsular Malaysia, this city is surrounded by satellite cities in Selangor State such as Batu Caves, Seri Kembangan, Ampang Jaya and Petaling Jaya.

3. Methodology
This study employed WRF-ARW model to simulate the air surface temperature and remote sensing technique to map the green area of Kuala Lumpur city as shown in Figure 1. The following subsections describe the steps involved to determine the relationship between green areas and air surface temperature of the Kuala Lumpur city. The steps involved were 1) Modelling the air surface temperature using WRF model, 2) Generating NDVI using remote sensing technique and 3) Determining the relationship between green areas and air surface temperature.

3.1. Air Surface Temperature Modelling Using Weather Research and Forecasting (WRF) model
In this study, the 2m air surface temperature was simulated using WRF Version 3.8 with Advanced Research WRF (ARW) core dynamic solver. The simulations were spun up for 24 hours for two different dates that coincide with the satellite images used in this study. Since the WRF-ARW simulation will only stabilize after 12 hours, this study runs the simulation for 48 hours for each year in order to simulate both dates well. Figure 1 shows the flow of the simulation employed in this study.

3.1.1. Domain Configurations. This study used four nested domains to simulate the 2m air temperature of Kuala Lumpur city with the grid size of 125km (30x30), 25km (51x51), 5km (131x131) and 1km (101x101). The dimension given in parenthesis is the number of grids in the easting and northing direction respectively. The area of the smallest domain (d04) covers the entire Klang Valley region where the Kuala Lumpur city is located as shown in Figure 2. NCEP FNL Operational Global Tropospheric Analysis data with a 1° by 1° resolution supplied by Global Data Assimilation System (GDAS) was utilized as the lateral boundary conditions every six hour interval. The common (default) WRF-ARW MODIS land use data available was used as to describe the terrestrial information of the Kuala Lumpur city.

Figure 1: Overall methodology flow of the study
Figure 2: Domain configuration
3.1.2. Physics Options Settings. WRF Version 3.8 offers a variety of multiple physics options, range from simple to very sophisticated schemes as well as newly developed and well-tried schemes which can be combined together to suit the study area needs. Based on the previous studies conducted [13, 16], this study employed the physics options as described in Table 1.

| Physics Option          | Scheme                  |
|-------------------------|-------------------------|
| Microphysics            | WRF Single-Moment 3-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     |

3.1.3. WRF-ARW Outputs Preparation using GIS Technique. Since the WRF-ARW outputs were stored in binary format (NetCDF files), this study employed GIS platform to prepare the WRF-ARW outputs before being used in the analyses. The air surface temperatures were extracted from the binary files using a special tool developed in ArcGIS software. The layers were then converted into raster data format which are easily to be manipulated in any GIS platform. Since WRF-ARW simulated and offered the air surface temperature in Kelvin (K), this study converted the air temperature values into degree celcius (°C), a commonly used unit for temperature in urban climate studies.

3.1.4. Model Validation. The air surface temperature simulated using the WRF model were validated against the ground observations provided by the Malaysian Meteorological Department (MMD). The ground observations on both dates collected from three stations which located in Universiti Malaya (03° 07' N, 101° 39' E), Subang (3°07’N, 101°33’N) and KLIA Sepang (3°06’N, 101°39’E) were used as the reference. Based on diurnal comparisons, the RMSE and R² of both simulated models were calculated to identify how well the model simulated the air surface temperature of the Kuala Lumpur city.

3.2. Generation of Normalized Difference Vegetation Index (NDVI)

In order to extract the green areas of the Kuala Lumpur city, two satellite images from Landsat 5 TM and Landsat 8 OLI were utilized. The images were captured on two different dates; 2nd of March 2006 and 29th of March 2016. These dates were chosen due to very clear sky view which reduces the chance of atmospheric error to occur during image processing.

The generation of NDVI value using Landsat 5 TM and Landsat 8 OLI employed two different bands called Near Infra-red (NIR) and Red band. The NDVI values within the study area were extracted using commonly used equation as stated in Equation 1. However, in order to use the equation, the digital numbers (DN) of each band should be converted into surface reflectance. The NDVI outputs from this process were classified into 3 classes as suggested by [11].

\[
NDVI = \frac{\rho_{NIR} - \rho_{Red}}{\rho_{NIR} + \rho_{Red}}
\]

where \(\rho_{NIR}\) = surface reflectance of NIR band
\(\rho_{Red}\) = surface reflectance of Red band

3.2.1. Conversion to Reflectance for Landsat 5 TM. The conversion of DN values into surface reflectance using Landsat 5 TM image involved two steps. At first, the DN values should be converted
into radiance using Equation 2. Then, the radiance values were converted into surface reflectance using Equation 3.

\[ L_\lambda = \left( \frac{L_{\text{MAX}_\lambda} - L_{\text{MIN}_\lambda}}{\text{QCALMAX} - \text{QCALMIN}} \right) \times (\text{CAL} - \text{QCALMIN}) + L_{\text{MAX}_\lambda} \]  

(2)

where \( L_\lambda \) = spectral radiance at the sensor aperture in watts
\( L_{\text{MAX}_\lambda} \) = spectral radiance that is scaled to QCALMAX in watts
\( L_{\text{MIN}_\lambda} \) = spectral radiance that is scaled to QCALMAX in watts
\( \text{QCALMAX} \) = the maximum quantized calibrated pixel value in DN
\( \text{QCALMIN} \) = the minimum quantized calibrated pixel value in DN

\[ \rho_\lambda = \frac{n \times L_\lambda \times d^2}{\text{ESUN}_\lambda \times \cos \theta_s} \]  

(3)

where \( \rho_\lambda \) = surface reflectance
\( d \) = Earth-Sun distance in astronomical units
\( \text{ESUN}_\lambda \) = Mean solar exo-atmospheric irradiances
\( \theta_s \) = Solar zenith angle in degrees

3.2.2. Conversion to Reflectance for Landsat 8 OLI. The conversion to surface reflectance of Landsat 8 OLI was using a different equation due to different sensor’s characteristics. The surface reflectance of Landsat 8 OLI can be obtained using Equation 4. However, the sun angle correction was calculated separately in Equation 5. The sun angle correction was performed after the bands involved were converted into surface reflectance.

\[ \rho_\lambda' = M_p \times \text{QCAL} + A_p \]  

(4)

where \( \rho_\lambda' \) = surface reflectance without sun angle correction
\( M_p \) = band-specific multiplicative rescaling factor from metadata
\( \text{QCAL} \) = Quantized and calibrated standard product pixel value
\( A_p \) = band-specific additive rescaling factor from metadata

\[ \rho_\lambda = \frac{\rho_\lambda'}{\cos(\theta_{SZ})} = \frac{\rho_\lambda'}{\sin(\theta_{SE})} \]  

(5)

where \( \theta_{SZ} \) = Local sun elevation angle
\( \theta_{SE} \) = Local solar zenith angle

3.2.3. Pixel Data Resampling. The original pixel size of Landsat 5TM and Landsat 8OLI was 30m by 30m which were not suitable to be compared to the simulated air surface temperature modelled by WRF-ARW. Therefore, resampling and aggregating the pixel size of the NDVI layers extracted from the satellite images were performed. The NDVI layers were resampled and aggregated into 1km by 1km resolution by assigning the mean NDVI value for each pixel.

3.3. Relationship between green areas and air surface temperature of the Kuala Lumpur City
The relationship between the green areas and air surface temperature of the Kuala Lumpur city was carried out using linear regression models. The study used pixel-to-pixel analysis to assess the effects of the green areas of air surface temperature within 1km by 1 km resolution. Through the linear
regression, the correlation between the green areas and air surface temperature were determined and presented using the value of goodness-of-fit for linear model ($R^2$).

4. Results and Analysis

4.1. Simulation Validation against Ground Observation

Based on this study, the RMSE of the model in 2006 were 1.9°C, 1.8°C and 0.8°C for Subang, Universiti Malaya and KLIA Sepang station respectively. Whereas, the RMSE of the model in 2016 were 1.9°C for Subang, Universiti Malaya and KLIA Sepang station respectively. Based on the RMSE tolerance, outstanding agreements between the prediction and ground observation were identified in this study for the year 2006 and 2016. Therefore, it can be concluded that the model employed in this study able to simulate the air surface temperature of the Kuala Lumpur city well. Figure 3 and Figure 4 illustrated the agreements on 2006 and 2016.

4.2. Air Surface Temperature of Kuala Lumpur City

The simulated air surface temperature distributions are shown in Figure 5 and Figure 6. From this study, it was found that, the air surface surface temperature of the Kuala Lumpur city was increased in the last decade. From the figures, it was also identified that the northwestern parts and some western parts of the Kuala Lumpur city are warmer than the others. This may be due to built-up coverage in the northwestern and western parts of the city which consist of mainly compact residential areas as compared to the other parts. Even though the eastern part is the busiest regions in Kuala Lumpur that includes the business areas and the city center, the areas were fragmented with green vegetation which makes the air surface temperature to be lower.

4.3. Green Area of Kuala Lumpur City

In Figure 7, the changes of green vegetation in Kuala Lumpur city can clearly be seen. In some parts, the green vegetation has become matured especially in Bukit Tunku and Mont Kiara with an increase of 5%. Also, it was found that, some vegetated areas have become mixed of built-up areas with vegetation portions. The conversion covered about 2.4% of the city areas. The decrease in 7.7% of cleared land and built-up areas was also identified in this study.
4.4. Relationship between Air Surface Temperature and Green Area in Kuala Lumpur City

This study has identified a strong correlation between the green areas and air surface temperature. In both years, the R² analyzed were 0.792 and 0.886 for 2006 and 2016 respectively. Figure 8 and Figure 9 show the correlation of green areas and the air surface temperature during the selected dates. A strong negative correlation indicates that the higher the NDVI values, the lower the temperature. Therefore, it can be suggested that, green vegetation has a positive impact towards the urban climate condition.
5. Conclusion and Recommendation

From this study, it has found that green area has a significant effect on air surface temperature. Strong negative correlation was identified through linear regression performed in this study. Therefore, it can be concluded that the green area contributes to the decrease in air surface temperature of the Kuala Lumpur city and can be used as an urban cooling agent.

Spatially, the distribution of green vegetation helps in reducing the air surface temperature within the city. The regions with matured green vegetation tend to have lower air surface temperature distribution as compared to the regions with compact built-up features. However, the study has also identified that the increase of 5% matured green areas for the Kuala Lumpur cannot stop the city to be warmer as a whole. Future studies should quantify the response of green vegetation towards the urban climate for better understanding and specific mitigation measures can be constructed.

Northwestern and some western parts of the Kuala Lumpur city are warmer than the eastern parts. This may due to different urban morphology and settings between both parts. The western part of the city consists of compact residential area, whereas the eastern part of the city consists of the city centre and business areas which have been fragmented with vegetation portions. Future studies should quantify the difference in reactions towards climate by different urban morphology and settings.

Green vegetation is only one urban parameter that impacts the urban climate. Future studies should look into other urban parameters in order to analyse the behaviour of Kuala Lumpur climate in detailed. This study suggests that, future studies on mixed built-up and vegetation areas should be performed to quantitatively identify the built-up area and green area effects on urban climate.

Acknowledgements

The authors would like to express their gratitude to the Universiti Teknologi MARA (UiTM) and Ministry of Higher Education (MOHE) for funding this project under the Research Acculturation Grant Scheme (RAGS) 660-RMI/RAGS 5/3 (66/2015).

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