Factors Contributing to the Formation of an Urban Heat Island in Putrajaya, Malaysia

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Abstract

This study investigates the alternative factors that induce the urban heat island phenomenon. The two approaches adopted in this study, are land use changes evaluation and historical climate data comparison. Land use/land cover and land surface temperature maps were produced in order to quantify the urbanization and its impacts towards the thermal behaviour of an urban area. The years 1999 to 2006 were seen as an urbanization period. Curiously, while urbanization continued in 2009, the surface temperature was actually lower than that of 2006; despite a consistent increase of vegetation. Hence, heat is not mainly regulated by the maturity of vegetation. It was also found that the sea level was notably high during 2006, suggesting that significant permafrost melting which was subsequently evident to the climate change effects. Therefore, the factors contributing to the formation of a UHI in Putrajaya were not solely caused by urbanization, but also due to other climate change effects.

1. Introduction

Energy and climate are highly associated with the built environment. Built environment is not only comprised of building collections, but also the physical results of various economic, social and environmental processes (Santamouris & Asimakopoulos, 2001). Urban micro-climate change effects can

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be seen when major cities experience the formation of urban heat islands, due to urban expansion, pollution growth, and the development of major industrial activities in metropolitan areas (Ghazanfari, Naseri, Faridani, Aboutorabi, & Farid, 2009). Urbanization promotes the changes of land use and land cover. Urban scale investigation of climate modification requires one to look into human activities. Human activities are a major influence of urban climate because the concentration effects of their activities may differ considerably from surrounding rural regions. Changes of land cover will relatively change surface properties, like heat capacity, heat conductivity, albedo, roughness length, maximum evaporative conductivity, heterogeneity, Leaf Area Index (LAI), and water features (Mölders, 2011). The dynamic interactions of these surface properties are shown in Figure 1.

The primary response of land cover change modifies thermal stratification and evaporation. These will definitely alter the atmospheric boundary layer temperature and moisture. The smallest change of land cover implicates the weather. Hence, it impacts the urban climate condition remarkably.

The urban heat island is the most obvious climatic manifestation of urbanization. Extensive previous studies have explored the causes and factors contributing to the formation of UHIs. One ideal resolution, summarized by Voogt & Oke (2003), included the following:

- Canyon Radiative Geometry - decreased long-wave radiation loss from within street canyons due to the complex exchange between buildings and the screening of the skyline.
- Thermal Properties - increased storage of sensible heat in the fabric of the city.
- Anthropogenic Heat - heat released from combustion of fuels and animal metabolism.
- Urban ‘Greenhouse’ - increased incoming long-wave radiation from the polluted and warmer urban atmosphere.
- Canyon Radiative Geometry - multiple reflections of short-wave radiation between the canyon surfaces decreasing the effective albedo of the system.
- Evapotranspiration - reduction of evaporating surfaces in the city, putting more energy into sensible heat and less into latent heat.
- Shelter - reduced turbulent transfer of heat from within streets.

Fig. 1. Primary, secondary and biogeophysical response of land cover change (adapted from (Mölders, 2011))
1.1. Climate change and heat island effects on human health and mortality

Climate change and changes of land use have similar impacts on society health and living. Both changes focus on the deterioration of ecosystem dynamics and its stabilization. Myers & Bernstein (2011) reported how global climate change may affect human health and nutrition resources. Many studies have outlined the direct impacts of climate change, such as heat stress (Heisler & Brazel, 2010; Li, Zhou, Ouyang, Xu, & Zheng, 2012), air pollution (Afroz, Hassan, & Ibrahim, 2003; Taha & Sailor, 2010), and the transmission of infectious diseases (Tomlinson, Chapman, Thorne, & Baker, 2011). Human health is affected by climate change through biogeochemical interactions and the presence of biological responses towards the climate and the atmospheric composition.

The formation of heat stress through the heat wave amongst humans may lead to more serious illnesses, such as heat stroke. Arneth et al. (2010) suggested that the biosphere influences, and to a certain degree, regulates atmospheric composition, chemistry, and climate change via biogeochemical feedback processes. Increased temperature can also amplify air pollution concentrations (Gartland, 2012; Roberts, 2004), and thus lead to the formation of major cardio respiratory allergies, such as asthma (Koken et al., 2003). Pollution also influences the climate of a city. Pollution particles reflect solar radiation, leading to a decrease in solar energy reaching the surface. Heat islands have been recorded as major urbanization effects. The mitigation of a heat island improves air quality in the following three different ways (Gartland, 2012):

- A cool environment will provide less demand for energy, and thus, reduce pollution from power plants
- Trees and vegetation help to improve the transportation of air pollutants, such as oxides of sulphur and nitrogen; thus reducing air pollution.
- With cooler air temperatures, the formation of fog is less.

The importance of having urban green campaigns and infrastructures was suggested to influence the urban community’s environment (Mansor, 2010). Outdoor participation leads to healthier lifestyles and helps to resolve the adverse effects of climate change, thus transforming the well-being of urban society and its environment. A major mitigation strategy, which has received global recognition and attention, is the escalation of surface cooling properties, which is the land surface albedo. Land surface albedo is suggested to have a direct relationship with surface heat (Jiang, Zhang, Gao, & Miao, 2007). Akbari, Matthews, & Seto (2012) discussed the effects and potential improvement of increasing this cooling biophysical property.

1.2. Rationale

The modifiable factors of climate change, urbanization, and the UHI phenomenon are an indication of the need to investigate whether a warmer city results solely from development and modernization; or are perhaps the effect of each other co-existing. Given the opportunity of having Putrajaya as a planned city; being built according to a series of comprehensive policies and guidelines for land use, the possibility to investigate whether such a well-structured city that holds a concept of greenery and climate adaptation, can still induce a UHI. Thus, the magnitude of urbanization amplifies the city’s emissions and the heat needs to be measured, and whether the UHI and climate change is a cycling effect, or does it come one after another, is a questionable issue. Measuring changes in satellite-derived land surface temperatures over time provides a quantitative means of tracking land surface change and measuring that change in terms that can be directly applied by global and regional climate change and ecosystem applications; particularly those which have to monitor energy transfer at the surface.

According to Mustafa (2009) Putrajaya was designed to suit; the topographical conditions, local climate, and cultural norms enriching the local urban form; the creation of an interesting cityscape; the
optimization of scenic panoramic views and spatial experiences; the promotion of local flora as a Malaysian landscape identity; the creation of a network of open spaces, and finally; the incorporation of intelligent buildings and infrastructural features. Contradictory to what was reported by Moser (2010), the climate is one of the primary challenges to urban designers and architects in Malaysia. One of Putrajaya’s main shortcomings is that climatic response in planning, architecture, and landscape architecture was minimal. With great design freedom, an expansive budget, and an explicit goal of creating a ‘garden city’, the designers for Putrajaya have missed an important opportunity to advance microclimatic design and create a ‘green’ city, cooled passively through design and planting, rather than relying primarily on air-conditioning. This claim is consistent with review made by Danby (1986) on the diversification of Islamic architecture in Arabic cities in promoting the passive cooling strategies. Moser (2010) asserted that Putrajaya’s designers failed to reclaim the use of urban microclimatic features that were developed in the Middle East to contradict the effects intense heat from a constant sun illumination (Hakim, 1994).

The green environment that transpires through many parks and gardens threaded throughout the city, only provide limited power in reducing the heat throughout the day. This is because the greenery areas consist of decorative landscaping features rather than huge canopies or long benches of trees. Not to mention the sidewalks throughout the city have very little vegetative cover at all, even until recent years. Perhaps, some of the issues raised by these authors should be taken into account. With all of the above mentioned factors, the Putrajaya area is eminently suitable for conducting this research.

1.3. Putrajaya geographical and topographical setting

Putrajaya sits at 25km south of Kuala Lumpur on a 50km stretch between Kuala Lumpur and Kuala Lumpur International Airport (KLIA). Located just a few degrees north of the equator, Putrajaya experiences the same climate conditions as other cities in Malaysia i.e., hot and humid all year round. Rainfall averages 2–3m per year and usually falls in heavy monsoons, depositing 10–30cm within just a few hours. The topographical conditions of Putrajaya may suppress air circulation and heat escaping smoothly from the surface.

2. Methodology

The method adopted in this study comprises the basic remote sensing imagery processes for extraction of land surface temperature, producing maps of Normalized Difference Built-up Index (NDBI) to measure the built-up index and Normalized Difference Vegetation’s Index, to measure the vegetation index, which is used to attune the land surface temperatures.

2.1. Land surface temperature (LST) extraction technique

Prior to extracting the LST, images were atmospherically corrected. The Dark Object Subtraction algorithm was applied by using the COST method (Chavez, 1996). Next, the parameters were translated into a Spatial Modeller, using the Erdas Imagine software. Two methods of LST extraction were applied in this study, known as Split Window (Mao et al., 2005) and Mono Window (Qin, Karnieli, & Berliner, 2001). Typical steps are similar in both methods, except for the final equation arrangements. The sequences can be seen in Figure 2.
2.2. Measuring vegetation and built-up areas

Two main equations were used to quantify the values of vegetation and built-up conditions in the study area. These equations are as follows:

2.2.1. Normalised different built-up index (NDBI)

The NDBI enhances the built-up features of the earth’s surface. It is an automated mapping of urban built-up areas. Using the same rationing technique as NDVI, the building and urban area’s reflectivity is more concentrated at the middle-infrared (MIR) band compared to near-infrared (NIR) (Zha, Gao, & Ni, 2003). Thus, the built-up land can be calculated using this equation:

\[
NDBI = \frac{MIR - NIR}{MIR + NIR}
\]

2.2.2. Normalised different vegetation index (NDVI)

The simplest form of vegetation index is a ratio of near infrared (\(\rho_{nir}\)) and red (\(\rho_{red}\)) reflectance, known as Simple Ratio (SR). For healthy living vegetation, this ratio will be high, due to the inverse relationship between vegetation brightness in the red and infrared regions of the spectrum. Based on geometrically corrected Landsat ETM+ images, the SR can be calculated using the reflectance of the near infrared band (\(\rho_{nir}\)) and is the reflectance of the red band (\(\rho_{red}\)). The Normalized Difference Vegetation Index (NDVI) is most commonly used vegetation index. It can be calculated by using this equation:

\[
NDVI = \frac{(\rho_{nir} + \rho_{red})}{(\rho_{nir} - \rho_{red})}
\]

2.3. Comparison of land use changes and Reports on Climate Change

The three dates selected for comparison are shown in Figure 3. These dates represent the study area’s pre-development, during development, and post development conditions. Topographical evaluation was performed by observing the elevation conditions of the study area to their neighbourhood area, temporal development, and urbanization process (pre, during, and post), and was conducted by comparative analyses of land use changes, land surface temperatures, Vegetation Index (NDVI), and Built-up Index (NDBI), and finally, a historical climate data comparison (rising sea levels and El Niño–Southern Oscillation (ENSO) incidents) was performed but limited to textual information and graphs from previously documented and endorsed reports.
3. Analysis and discussion

The analyses were divided into two subsections. The first section presents the time series analysis of land use changes, LST, NDVI, and NDBI. The second section looks at climate change reports, documented to verify the existence of climate change influenced by the UHI phenomenon; elaborated and discussed from the first section. Figure 4 shows LSTs of 1999, 2006 and 2009.

The UHI intensities for 1999, 2006, and 2009 were 5.73, 6.75, and 5.91 degrees Celsius, respectively. The highest intensity (in 2006) shows the multiplication of urbanization activities that amplified the surface temperature of the study area. The declinations in 2009 initiated the need for this study, and at this time, several investigations were conducted. The following sections explain several contributions to the formation of a UHI in Putrajaya.

3.1. Section 1: land use changes, LST, NDVI, and NDBI for 1999 to 2009

Significant increases of urban and developed areas can be visually recognized. This is supported by a remarkable increase of the built-up index of the study area, as well as the reduction of the vegetation index signatures as shown in the NDVI maps. Table 1 explains the percentage changes of five major land use classes in the study area.
Table 1. Percentage changes of land use

| Land Use   | 1999 Area (acres) | 1999 % | 2006 Area (acres) | 2006 % | 2009 Area (acres) | 2009 % |
|------------|-------------------|--------|-------------------|--------|-------------------|--------|
| Water bodies | 274.88            | 1.395  | 408.32            | 2.073  | 259.090           | 1.315  |
| Clear land  | 1853.89           | 9.411  | 1505.61           | 7.643  | 966.084           | 4.904  |
| Urban       | 8723.00           | 44.282 | 11842.76          | 60.119 | 12699.640         | 64.469 |
| Forest      | 4356.28           | 22.114 | 1975.31           | 10.028 | 1007.227          | 5.113  |
| Vegetated/Green | 4490.82       | 22.797 | 3966.86           | 20.138 | 4766.812          | 24.198 |

Aggressive urbanization activities took place between 1999 and 2006; as demonstrated by the percentages of urban and bare land areas being increased, whilst the vegetated and forested areas fluctuated remarkably. Figure 5 shows the land use maps of the study area, tagged with their NDVI and NDBI maps. The land use map clearly show the reduction of vegetations area (appear in light and dark green) and it is highly consistent with the NDVI. The NDBI representation indicates that clear land (pink)
has switched into highly built up area (brown to grey) exhibited the urbanization and development has taken placed. One of highly influenced area can be seen marked in black circle in Figure 5 (though the rest of the study areas have significant spatial contribution to this study). Figures 4 and 5 clearly show that urban areas that include governmental office buildings, commercial, and residential land exhibited the highest temperatures, followed by cleared land and open spaces.

Figure 6 illustrates the land use and land cover areas of Putrajaya. As can be seen, the urban areas increased consistently over the years, in agreement with the reduction of forested areas. The green areas in this graph represent vegetation and landscape features, which show an increase of green feature’s maturity at three different timeframes. Hence, greenness can be concluded as a cooling element of this particular urban area.

Even though urbanization expanded each year; by 16% in 2006 and 5% in 2009, forested areas seemed to be the main casualty as 22% of these initially forested areas were decreased to just 5%. 2006 showed signs of devastation, with a 12% and 3% reduction in forested and green areas, Putrajaya managed to recuperate the situation in 2009. The green areas managed to counterbalance the adverse effects of urban deforestation. Hence, land surface temperatures were at a peak in 2006, with a maximum temperature of 38°C, lowering to 34°C in 2009.

![Graph showing land use and land cover areas of Putrajaya](image)

Fig. 6. Land use and land cover area (acres) and percentages of 1999, 2006 and 2009

3.2. Section 2: climate change reports and events comparison

Published reports and papers on climatic events by other researchers and respective organizations were used in this finding to identify the coherence of results in Section 1. The three selected dates used for comparison in this study were captured during the North East Monsoon (wet period). However, several climates and monsoons needed to be considered (Indian Ocean Dipole (IOD), El Nino-Southern Oscillation (ENSO), and Madden-Julian Oscillation (MJO)). The IOD and ENSO occurred at Inter-annual oscillation (2 to 7 years) while MJO at intra-seasonal oscillation (20 to 60 days). The IOD brought neutral conditions to the Malaysian region while ENSO led to extreme conditions of wet (La-Nina) and dry (El-Nino). Reports show that two extreme events of ENSO occurred in 1998 (El-Nino) and 1999 (La-Nina). The study period was categorized as being one of the hottest years, according to global average temperatures recorded between 1850 and 2010 (see Figure 8). This is in line with the results of this study, where the surface temperature ranged from 22°C to 38°C between 1999 and 2009. Curiously, in this study, the temperature decreased in 2009 in spite of the constant growth of urbanization activities and linearly increased temperatures globally. As such, a regional approach case study was looked into. For
this instance, another aspect that resulted from global heating was the rise of the sea level, due to permafrost ice melt (Gregory & Oerlemans, 1998). This was also explored.

Fig. 7. Global average surface temperatures (MMD, 2012)

Sea level has been linked to global temperature, where a simple simulation was tested and showed a strong correlation that explained 98% of the variance (Vermeer & Rahmstorf, 2009). The sea level in 2006 (NASA, 2013) may have contributed to the increased surface temperature in that year. The sea’s surface temperature was also remarkably high in 2006. This was possibly caused by the late onset of the northeast monsoon, which brought heavy rainfall during mid-Dec 2006. It was also reported that major synoptic features contributed to heavy rainfall episodes during the northeast monsoons of 2006/2007 and 2007/2008 over Malaysia. The late onset of the northeast monsoon in 2007/2008 caused heavy precipitations over Malaysia until the end of 2008 (MMD, 2009). Thus, the declining surface temperature shown in 2009 was reasonable. Green space was seen as being valuable in helping to ease the 2009 urban temperature. The sea level was also seen to be lower in 2009 (NASA, 2013). Through these seasonal and extreme events, the inclining and declining temperature in 2006 and 2009 was highly influenced by green space and climatic response.

4. Conclusion and recommendations

Even though many suggested environmental degradations have major links with modernization and urbanization, this study reported that a city built with environmental awareness and planning wisdom cannot escape the impacts of climate change. We conclude that climate change strategy for adaptation and mitigation is crucial in educating society to lead a green lifestyle. Mitigating and recuperating the environment need to be enforced at a vast scale to ensure the efforts of having environmental friendly urban areas can be materialized without having external moderators to cancel out the hard work of environmental scientists and planners to produce a climatic friendly development plan. The proposed climate combat and adaptation strategy framework for urban environments, which involves three phases, is shown in Figure 8.

Fig. 8. Urban climatic response strategy framework
In this case, it is best to improve and modify what has already been built, rather than totally demolish it. This stage is best referred to as the corrective age. The resolution of Putrajaya Green City 2025 greatly depends on this corrective period; as building and enforcing new green integrated developments can only be complimented if the existing mess and adversity is being rescued and neutralised. The efforts of having and achieving a green city lifestyle will fall short if climate change effects go riotous without recuperation or rectification. The LULC change and landscape pattern alteration, which responded to the urbanisation phases, cannot be totally halted. However, it requires sustainable planning and management to protect the balance of urban biogeophysical and biogeochemical properties while urbanization takes place. In looking at the cross calibration of climate changes and seasonal event reports, it is recommended to use primary data to endorse and ratify these findings further.

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