How Does Urban Development Contributes to Urban Heat Island: A Decade Increase of Urban Heat Intensity in Jakarta Metropolitan Area

Sofi Ulfiasari and Lin Yola

Abstract Rapid Population growth and economic movement have had a significant impact on the social and environmental change of Jakarta. The dense development of Jakarta goes horizontally and vertically in the city center. The trend also expands and encourages the interaction between the city center and the buffer cities within the Jakarta Metropolitan Area. As a result of the intense socio-economic activities in the city center, the phenomenon of Urban Heat Island (UHI) emerges as the city issue. The rapid increase of UHI intensity worsen the and climate change and is a challenge for Jakarta in realizing a sustainable city agenda. This study indicates a lacking of the focused investigation on the correlation between urban development and UHI in Jakarta Metropolitan area. Therefore, this study aims investigates a decade by using the analysis of Landsat 5 and 8 satellite imagery asses the building density index value and albedo. The variables include the land surface temperature, vegetation index, land cover and satellite light imagery. This study pinpoints the significant impact of urban development on the UHI intensity. The results of this study provide scientific contributions to academia, industry and city governments in the formation of a policy framework for the UHI and climate change mitigation agenda in Jakarta.

Keywords Albedo · Building density index · Jakarta metropolitan urban development · UHI

1 Introduction

Jakarta Metropolitan Area, locally known as 'Jabodetabek' dated from 1997 with strengthening and concentration of the economic concept is the capital city that, handle 50% of circulation of state finances [1] and now became a largest

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metropolitan area in Indonesia with 6 cities in 3 provinces. In 2019, the Jakarta population a central of Jabodetabek has reached 10.5 million [2]. This trend raises environmental issues, especially the increase in urban air temperature, which is one of the main contributors to climate change. In this context, one of the focus issues that need to be targeted for a solution in Jakarta is the Urban Heat Island (UHI) phenomenon. The temperature increase in the city area significantly affects the level of thermal comfort and the energy consumption. A 0.03 °C yearly temperature increase accelerates atmospheric modification conditions [3].

UHI is defined as the temperature increases in urban areas compared to the surrounding environment that starts after sunset [4–6]. UHI can achieve a maximum temperature rise of 5.6 °C in urban zones [7, 8]. While the temperature difference between urban and rural can reach 12 °C in a metropolitan city [9]. Jakarta's surface temperature can exceed 34 °C which reaches the highest level 3–4 h after sunset in downtown Jakarta [10]. Jakarta experienced the highest temperature increase (0.82 °C). In 2019, the year that experienced the second highest temperature rise after the 2016 phenomenon, compared to the temperature vulnerability of 1981–2010. This illustrates that UHI is a significant issue that requires urgent solutions in Jakarta Metropolitan Area, because the UHI issue is one of the main challenges in realizing the climate change mitigation agenda. If this phenomenon continues, it will give an impression of an increase in global temperatures [11].

The factors that cause UHI [12] are increased anthropogenic heat, reduced evaporation, increased heat storage, increased radiation and reduced convection. In addition, population and urban density measures will also affect the intensity of the urban heat island [7]. Asian cities are growing with increasing population and city size rapidly, due this situation there is any variation and trend changing in urban heat island [13]. Populations may also track the trailing climate through migration or dispersal, or they may go extinct [14].

The increase in the intensity of the UHI is a variable that cannot be separated from the discussion of climate change mitigation. Reducing increased emissions is one of the national targets on the agenda in the National Action Plan for Reducing Greenhouse Gas Emissions (RAN-GRK), as a follow-up to Indonesia's commitment to dealing with climate change issues. However, there is lacking of the intensive studies on the past decade on UHI in Jabodetabek. Therefore, this study aims to provide a study on the mapping of UHI as a measure to mitigate the intensity of UHI in the Jakarta Metropolitan Area, the largest metropolitan area facing the highest UHI issue in Indonesia today. The use of remote sensing images is able to obtain the intensity and distribution of UHI temporally [15]. So that UHI detection can be done in a relatively short time compared to having to measure in the field [16].

2 Literature Review

2.1 Urban Climate

Urban climate is the result of the interaction between the urban surface and the lower atmospheric layer which takes place radiatively, thermodynamically, and aerodynamically so that it can change surface temperature, air temperature, humidity, rainfall, air quality, surface energy flux, mixing layer height, boundary layer wind, and turbulence in urban areas [17]. Urban Heat Island is a characteristic of high temperature that is concentrated in an urban area [16]. Urban Heat Island arises because the isotherm pattern forms an island-like pattern. The temperature difference between urban and rural can reach 12 °C in a metropolitan city [9]. Urban Heat Island occurs as a result of changes in temperature, albedo, evapotranspiration, and energy flux [12]. This phenomenon is a clear example of humans being careless in modifying the climate [18]. According to Oke [7] and Sobrino et al. [19], the spatial and temporal characteristics of UHI vary widely depending on local changes in urban form and function. The size of the UHI is also strongly influenced by local meteorological conditions and geography (topography, presence of water bodies such as lakes or rivers, soil types, etc.) of the local area. In addition, population and urban density measures will also affect the intensity of the UHI [7].

Microclimate scale urban heat island have been frequently associated with global warming [20]. The urban heat island effect resembles a system that makes urban residents need air conditioning, while air conditioning will increase electricity consumption and can contribute to urban heat. Some of the negative effects of urban heat island among them the deaths of hundreds of people in the summer caused by heat wave [21]. The energy consumption is high in the area with high UHI variations and the other way around [22]. The rising greenhouse gas concentration cause an elevation in temperature at both urban and less urbanized area direct urban heat island to increase [23]. Currently, human activities are no longer limited to only in the morning, technology has helped humans to move into the night, this has led people, especially in urban areas, to use it to continue producing even up to 24 h [24].

2.2 Urban Development

With the background of rapid urbanization, the population living in urban areas is forecasted to be 5 billion by 2030 [25]. Urban development cause urbanization and migration of population from rural to urban areas, this phenomenon isolated population centres are changing into metropolitan cities and still growth because urban development was viewed as an end result of human actions, and the value system of urban society as the primary source of the impulse for actions [26] Urban sprawl is the phenomenon of disproportional expansion of urbanized areas into undeveloped land [27].

Human activities on earth inevitably affect land cover which refers to the physical and biological cover above the soil surface, including water, vegetation, vacant land and/or artificial structures [28]. Numerous modifications of land surface will occur as an accumulating number of people migrate into metropolitan areas [29]. So that one indicator of the UHI is the amount of waterproof material can store heat [30].

The configuration of spaces and buildings in the dense urban area plays a significant role in the urban microclimate and outdoor activities [31]. The solar radiation trapping effects in urban spaces depend on urban configuration, vertical obstruction and roughness play roles of creating shadow effect [32]. The presence of natural vegetation influenced a lot in the distribution of Land Surface Temperature [33].

3 Methods

The computer simulation is a reliable tool to climatically responsive urban configuration study, technology helped climate study more effective and efficient [34]. Surface Urban Heat Island first observation from satellite-based sensors in 1972 and landsat is the one which has thermal sensor which can provide temperature in real time [16]. The difference daytime and nighttime urban heat island is the anthropogenic heat had bigger effect at night, based from computer simulation [35]. So that, in this study using nightlight imagery satellite to provide how heat produce at night that can increase heat storage. To detect surface urban heat island and its correlation with urban development, built-up index, green index and city light are needed to correlate with surface temperature.

This study was conducted in the area of Jakarta metropolitan area (Jabodetabek) situated at 3 province which are DKI Jakarta, West Java, and Banten. A fullscene Landsat 5 and 8 (path 122 row 64 and 65) of 2009/07/29, 2014/9/13 and 2019/8/1 were acquired with a little cloud cover. The very high resolution (VHR) imagery was used to calculate the percentage of a Normalized Difference Built-up Index and land surface temperature. Nightlight satellite data image from NOAA of 2014/7/1 and 2019/4/30 was used to extract city light.

The formula for calculating LST For Landsat 5,

$$\text{Radiance} = \frac{\text{LMAX} - \text{LMIN}}{\text{QCalmax} - \text{QCalmin}} \times (\text{QCal} - \text{QCalmin}) + \text{LMIN} \qquad (1)$$

where the gain and offset can be obtained from the header file, Qcalmin = 1, Qcalmax = 255, Qcal = DN, and Qmax and Qmin.

For Landsat 8 Using the radiance rescaling factor, Thermal Infra-Red Digital Numbers can be converted to TOA spectral radiance.

$$L\lambda = ML * Qcal + AL \quad (2)$$

where

$L\lambda$ = TOA spectral radiance (Watts/(m^2.sr. μm))
ML = Radiance multiplicative Band (No 10)
AL = Radiance Add Band (No 10)
Qcal = Quantized and calibrated standard product pixel values (DN).

Spectral radiance data can be converted to top of atmosphere brightness temperature using the thermal constant Values in Metadata file,

$$T = \frac{K2}{In\ (K1/L\lambda) + 1} \quad (3)$$

where T is the effective at-satellite brightness temperature in Kelvin, K1 = 666.09 (m.W.cm^{-2} . r^{-1}) and K2 = 1282.71 K are calibration constants, and TTM6 is the spectral radiance in m.W.cm^{-2} . sr^{-1}.

The formula for calculating Normalized Difference Built-up Index as follows [36]. Simply, in the NDBI image the built-up area and barren pixels have a positive values, whereas the negative or zero values mean other land covers, allowing the built-up regions to be set automatically.

$$NDBI = \frac{SWIR - Nir}{SWIR + Nir} \quad (4)$$

Normalized Difference Vegetation Index shown biomass and vegetation health index [37] which has correlation with land surface temperature [38]. The formula of NDVI has result from −1 to +1, means no vegetation to highest possible density of green leaves [39]

$$NDVI = \frac{Nir - Red}{Nir + Red} \quad (5)$$

To understanding the correlation between land surface temperature, build-up area and city light, the approach is used to estimate correlation on the linear regression model as follows:

$$Y = a + bx \quad (6)$$

4 Result and Discussion

4.1 Urban Development

Being the capital city of Indonesia, the sprawling metropolitan city of Jakarta is the centre of government as well as business activities in Indonesia. Jabodetabek is a metropolitan district dated 1997 became the fastest growing city in Indonesia and the world's second-largest conurbation, the development in every city and its integration through infrastructure creates more and more built-up areas. Urbanization occurred in every region, until it spread closer to Jakarta. Data processing Landsat satellite imagery using SWIR and NIr sensors produces built-up index to show how the cities grown.

At last, 10 years development in Jabodetabek, built-up area growth 250% from west to east, high density built-up area growth up to 500% from 2009 to 2019 and found in core cities (Fig. 1). Built-up area growth following the infrastructure and access, the low density shown increasing new housing in the suburbs. The high density built-up means more areas covered by high buildings which can indicate as a characteristic of a metropolitan city. The high density building found in North Jakarta at 2009 and grows in Tangerang (westside) until Bekasi (eastside) at 2014–2019. High density built areas grew rapidly in Tangerang and Bekasi, in 2009 there was a low density, then changed to high density in 2014 so that the surrounding area turned into a built area with low density (Table 1).

National Oceanic and Atmospheric Administration produce nightlight satellite imagery that can shown city light as a product of human activities at night (city light) shown in Fig. 2. City light comes from the use of lights in built-up areas, lights that come from vehicles and objects that radiates heat.

In 2014, there were high brightness reaching 640 nW/cm^2/sr, but in 2019 the highest brightness level was only 385 nW/cm^2/sr. Figure 2 shown that Jakarta as a core and the city light is fading away from the centre, straight line pattern (road)

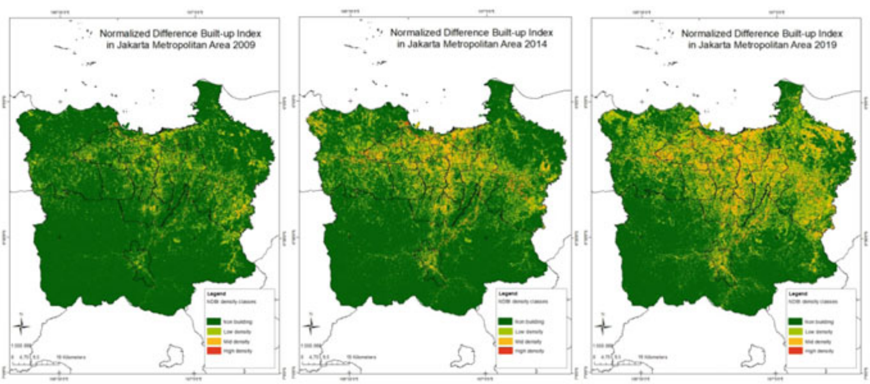

Fig. 1 Jakarta metropolitan area normalized difference built-up index 2009, 2014 and 2019

Table 1 Normalized difference built-up index area

No	Value	Dense index	km^2 (2009)	km^2 (2014)	km^2 (2019)
1	<0	Non building	5855.17	5246.40	4406.74
2	0–0.1	Low density	795.57	1080.14	1518.74
3	0.1–0.2	Mid density	153.773	445.10	840.14
4	0.2–0.3	High density	9.45	42.23	47.52

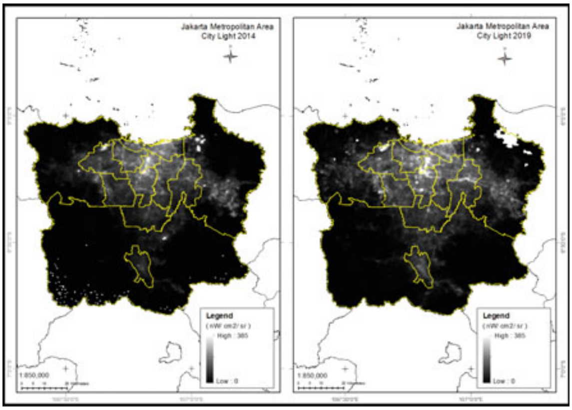

Fig. 2 Jakarta metropolitan area city light 2014 and 2019

with high brightness from the centre to the east. In 2019, city lights appear stronger and flatter, the light connected each region and the most brightness is in each core. In 2014, the highest city light appears when traffic jam at the core of the city but in 2019, city light spread up rapidly from the core (Jakarta) to the suburbs (west-east).

Spatially, NDVI that is shown in Fig. 3 in Jakarta Metropolitan Area non vegetation found in coastal areas, in 2009 the data was taken at harvest time so that

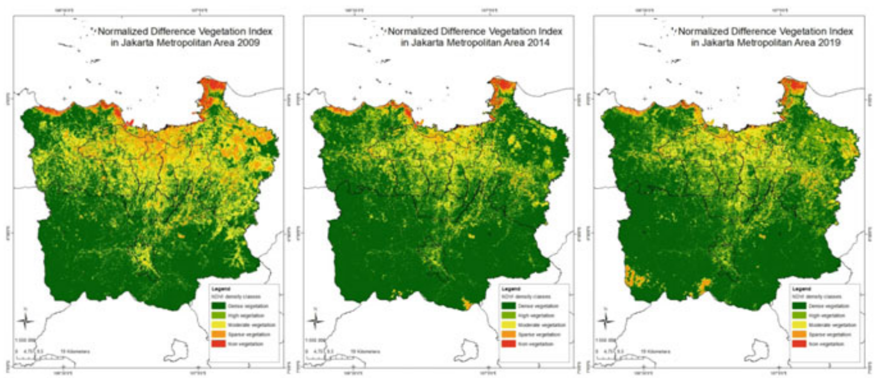

Fig. 3 Jakarta metropolitan normalized difference vegetation index 2009, 2014 and 2019

Table 2 Normalized difference vegetation index area

No	Value	Dense index	km^2 (2009)	km^2 (2014)	km^2 (2019)
1	<−0.03	Non vegetation	90.64	134.21	106.39
2	−0.03–0.15	Sparse vegetation	611.45	222.95	267.62
3	0.15–0.25	Moderate vegetation	867.37	647.97	818.43
4	0.25–0.35	High vegetation	866.71	830.67	1060.61
5	0.35–1	Dense vegetation	4341.68	5023.27	4606.04

the level of greenness was relatively low even though the three data were recorded during the dry season (Table 2).

4.2 Urban Heat Island

Jakarta Metropolitan Area LST distribution ranges from 0 to 40 °C with a centralized pattern in Jakarta and evenly spreads to its suburbs. Urban heat island occurs as a result of urban growth that is getting faster and wider in suburban areas. In 2019, the temperature distribution approaching 40 °C is in the Jakarta area as a whole and there is a line pattern that stretches from south to north that divides the centre of Bogor City of Jakarta according to the main road (Fig. 4).

The temperature value in suburban areas ranges from 18–34 °C, sub-urban areas that have a relatively flat altitude and the same as Jakarta have a temperature difference of up to 5 °C, while for areas that have a different altitude, the temperature difference reaches 10 °C. When viewed from the distribution pattern, the highest temperatures occur in areas with the highest human activity such as in areas

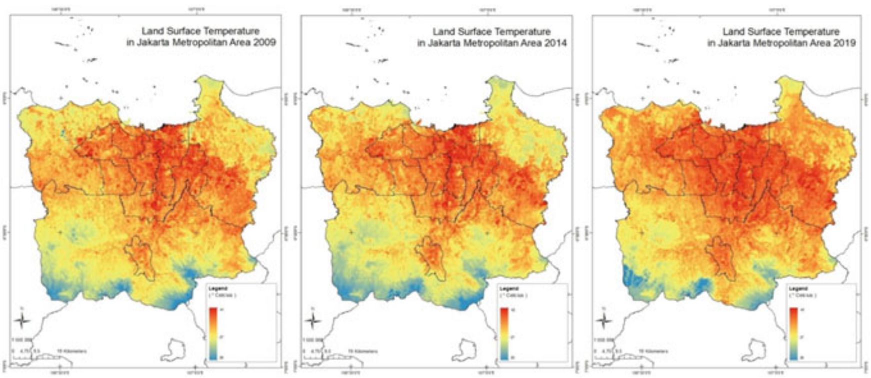

Fig. 4 Jakarta metropolitan area land surface temperature in 2009, 2014 and 2019

Table 3 Land surface temperature's correlation

Correlation	2009	2014	2019
LST and NDVI	LST = −8.0566 NDVI + 32.687 (r^2 = 0.3108)	LST = −8.0495 NDVI + 32.687 (r^2 = 0.3248)	LST = −8.6952 NDVI + 34.559 (r^2 = 0.2574)
LST and NDBI	LST = 13.514 NDBI + 31.921 (r^2 = 0.5058)	LST = 15.13 NDBI + 30.68 (r^2 = 0.5137)	LST = 17.173 NDBI + 31.672 (r^2 = 0.4601)
LST and City Light		LST = 0.2864 City Light + 27.061 (r^2 = 0.4417)	LST = 0.1865 City Light + 28.687 (r^2 = 0.3847)

around transportation routes, downtown areas and industrial areas. The minimum and maximum land surface temperature in Jabodetabek increase 3–5 °C at last 10 years (Table 3).

Correlation analysis has been done to find out the relationship between LST and NDVI which have shown a negative correlation, land surface temperature will lower if the dense vegetation is high. The city lights only have a small impact as temperatures at night, this variable can show how the cities works for 24 h, which can contribute to warming when the UHI occurs at night. Electricity and vehicle consumption at night shows a correlation with temperature. However, conditions that are too small in scale cannot provide detailed data so it is necessary to calculate electricity consumption and exhaust gas results in vehicles at night. NDBI and City light are the factors that influence the land surface temperature seen in the positive correlation results. NDBI correlated by 50% and City light correlated by 40% in increasing land surface temperature, while NDVI has a negative correlation means when NDVI increases, the temperature will decrease.

5 Conclusions

The urban temperature in Jabodetabek has reached over 30 °C is a real threat to not only city thermal comfort but also the energy consumption. This study points out that there is a rise of UHI intensity from 2009 to 2019 in the past decade. Economic activity is the biggest cause of accelerated temperature rise, changes in land cover make heat storage more widespread. City lights at night only account for 20% of the increase in temperature. Concentrations of City light brightness occur in City centers and streets (straight line) indicates the traffic jam, that may cause the temperature rising. Built-up area increasing 500% in a decade from west to east, the highest density found at North Jakarta, Tangerang and Bekasi. This phenomenon will make the urban climate system rapidly change. Built-up area increasing electrical consumption that increasing city light and heat storage in city, when the heat sorage larger than the ability of vegetation to absorb heat. So that vegetation in city can't withstand increasing land surface temperatures. The finding of this study is a significant reference for UHI and climate change mitigation national agenda to enhance the movement towards the cities sustainability targets.

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