Urban Form Factors that Play Important Roles on UHI Spatial-Temporal Pattern: A Case Study of East Surabaya, Indonesia

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Abstract. Urban Heat Island (UHI) has a negative effect on the local climate and ecological environment. On the other hand, urban form has an impact on the urban thermal environment. However, the relationship between UHI's temporal spatial pattern and the urban form is still unclear. Our research explores the distribution patterns of UHI in East Surabaya based on surface temperature data calculations from Landsat imagery in 2001-2019 every 5 years. The results show that have been inconsistencies in the UHI pattern over the past 18 years and the most significant change occurred in 2016 and 2019. There is a difference in the intensity of UHI between built up area and non-built up area. Factors that are characteristic of urban form include urban green infrastructure, urban geometric and urban material with their respective variables. Using spatial regression OLS (Ordinary Least Square) variables that affect UHI include albedo type, sky view factor, building density, urban green space and urban water space. The mean building high variable has a negative correlation with UHI, this explains that the higher the building does not necessarily affect the increase in urban temperature. Our research can be a reference in formulating UHI adaptations.

1. Introduction

Urban areas have characteristics to develop rapidly, accompanied by local climate change due to increased energy needs and concentration of pollution[1]. Climate change that occurs in the form of increased temperatures in urban areas compared to the surrounding area, known as Urban Heat Island (UHI)[2]. Many factors could affect the UHI intensity, one of them is the urban form. There are categorized as urban green infrastructure, urban geometry and urban material [3]. Urban green infrastructure consists of urban green space and urban water space[4]. Urban geometry consists of sky view factor, building density and mean building high[5]. Urban material in the form of thermal admittance and albedo surface[6].

Temporally, the East Surabaya area in 2001-2016 experienced an increase in temperature of 6.62°C[7]. This condition indicates that the change in surface temperature is the most significant compared to other areas of Surabaya City [8]. As a result, the conversion of open space into built-up area of 1376 hectares massively [9, 10]. The development of large scale buildings and high density will limit the sky view factor, which results in temperatures likely to be trapped [11]. The composition of the
material has a higher heat absorption such as asphalt, concrete, zinc and paving[10]. So, this condition creates thermal discomfort [12].

Therefore, urban forms have a profound impact on the urban thermal environment and urban sustainability [13]. This problem becomes very important because it is almost impossible to significantly change the urban physical. The built up area is largely irreversible and its modification required a high cost[14]. From this urban transformation, spatial temporal observation using LiDAR and Landsat imagery is needed to identify anomalous temperature increase[15]. This is because the previous research was only oriented towards UHI in the last year. Researchers observed that many studies related to urban form were only oriented to sample areas, but with the use of LiDAR, all urban physics could be modelling accurately in 3D. Through the analysis of factors that influence UHI can be considered in the formulation of the concept of adaptation[16]. In this study, we aim to discuss how the temporal spatial patterns of UHI change using remote sensing and the relationship between urban forms factors and UHI.

![Figure 1. Research position](image)

2. Theory

2.1. Surface UHI

Surface UHI are the surface temperature of urban areas that is higher than rural areas and are usually illustrated by thermal images. It can be said that the UHI surface can be observed on a local scale because it is a one-way view and based on the reflection of the object with the image. Different from the atmospheric UHI which is more likely to be at air temperature.

![Figure 2. Phenomenon UHI](image)

2.2. Urban Form Factors

Urban form factors in UHI surface research are closely related to urban physics. Urban form indicators that affect the UHI consist of urban size, urban geometry, and urban vegetation [3]. Some of the factors show a pattern that the closer to the variable the lower the temperature in the region.
Table 1. Urban form factors

| Factors                  | Variable                | Definition                                                                 |
|--------------------------|-------------------------|-----------------------------------------------------------------------------|
| Urban Green Infrastructure| Urban Green Space (UG)  | Green Open Space, Rooftop Greening, Tree, Vertical Greening                 |
|                          | Bluespace/Urban water   | River, Boezem / Lake, Pound                                                  |
|                          | Space (UB)              |                                                                             |
| Urban Geometri           | Building Density (BD)   | The percentage of land surface covered by buildings in a land lot.           |
|                          | Mean Building High (MH) | Mean building height in a land lot.                                         |
|                          | Floor Area Ratio (FAR)  | The ratio of the total floor area to the land area of a land lot.           |
|                          | Sky View Factor (SVF)   | The ratio between the radiation received by a planar surface and the entire hemispheric radiating environment |
| Urban Material           | Albedo Radiance         | Reflected heat by surface type                                              |
|                          | Thermal Admittance      | Absorbed heat by surface type                                               |

Each city has different urban form characteristics. In other words, not all variables from the literature will affect the UHI in the city of Surabaya. Thus, this study will examine how much the relationship between each urban form variables that play important roles on UHI.

3. Method

3.1. Spatial Temporal Urban Heat Island distribution

3.1.1. Land Surface Temperature form Landsat. Landsat imagery is a high quality multi-spectral image of the earth’s surface created by the National Aeronautics and Space Administration (NASA) and the United States Geological Survey (USGS)[18]. Landsat 7 ETM+ imagery is used for surface temperatures in 2001, 2006 and 2011. Landsat 8 images are used to obtain surface temperatures in 2016 and 2019. Processing begins with geometric corrections and radiometric corrections. Continued calculation of the value of radiance, reflectance value (ToA), value of brightness brightness temperature (BT), land surface emissivity (ε), and land surface temperature (LST) value by referring to the formula from the Landsat handbook [19, 20]. The surface temperature approach is used based on the formula of normalized difference vegetation index (NDVI).

3.1.2. Urban Heat Island Value. By referring to the definition of UHI from Howard (1998), there is deviation of temperature urban dan sub urban. Calculation of intensity and spatial distribution of UHI is done by explaining the value of surface temperature using a 3 x 3 filter in the local neighbourhood, to change the value of the pixels in the middle of the environment based on local pixel environmental statistics. To facilitate identification spatial temporal of LST, the data is classified in the form of a 500m2 grid[5]

\[
\Delta T_{\mu-r} = T_\mu (urban) - T_r (suburban)
\]  
(1)

\[
T > \mu, 0,5 \alpha and 0 < T \leq \mu, 0,5 \alpha
\]  
(2)

\[
UHI_{maps} = T_{mean} - (\mu, 0.5 \alpha)
\]  
(3)

Equation (1) is formula intensity UHI. Where $T_\mu$ is the urban surface temperature, $T_r$ is the suburban surface temperature, $\Delta T_{\mu-r}$ is the effect UHI. Equation (2) is value max and min UHI. Where $T>$ is the temperature threshold for the area in which the UHI results from neighbourhood filter, $0< area$ non-UHI, $\mu$ mean Land Surface Temperature, $\alpha$ standard deviation. Equation (3) is formula maps distribution UHI using NF 3X3 [21].
3.2. Urban Form Characteristics

3.2.1. LIDAR Ground and Non-Ground Imagery. This is an optical remote-sensing technique that uses laser light to densely sample the surface of the earth, producing highly accurate x, y, z measurements. This technology produces a cloud point with a detail of 0.3333m that can be used to create digital elevation models [22] from ground data and digital surface models (DSM) from non-ground data. Calculations DSM less DEM can describe the geometric size of buildings. So that the sky view factor value, building density, and building mean high can be obtained. Sky view factor is the ratio of the sky seen at the point of observation. LIDAR data can also provide information on the distribution of vegetation.

$$BD = \frac{\sum_{i=1}^{N} C_i}{C_L}$$  \(4\)

$$MH = \frac{\sum_{i=1}^{N} C_i H_i}{\sum_{i=1}^{N} C_i}$$  \(5\)

$$SVF = 1 - \sum_{i=1}^{N} \sin^2\beta_i \left( \frac{\alpha_i}{360} \right)$$  \(6\)

Equation (4) is formula of building density. Equation (5) formula of mean building high. Equation (6) formula of sky view factor. Where \(C_i\) is the coverage area of the building, \(C_L\) is the area of the land lot, \(H_i\) is the building height, \(N\) is the total number of the angle elements of the obstacles, \(\alpha_i\) and \(\beta_i\) reflect the elevation and azimuth angles of the angle element “i”[5].

3.2.2. High resolution aerial photography. Using LIDAR aircraft, aerial photographs were also extracted with resolution densities reaching 0.3333m. Through digitation on screen, thermal admittance, albedo surface, open green space and open blue space data can be obtained. The data is supported by existing spatial governance documents in the East Surabaya area, including the open green space master plan and detailed spatial plans.

3.3. Data Analysis

The first stage, to determine the variables that significantly influence to the urban heat island, a stepwise analysis was used. This analysis was performed using the exploratory regression toolbox in ArcGIS. This exploratory regression work system is to evaluate all possible combinations of input candidate explanatory variables, looking for the OLS model that best explains the dependent variable in the context of user-defined criteria. Ordinary Least Square (OLS) regression analysis is used to obtain the relationship between urban form factors and UHI. OLS is a regression analysis of the dependence of one dependent variable (bound) with one or more independent variables (independent variables), with the aim of estimating and or predicting the population average or the average value of the dependent variable based on the value of the independent variable known spatially. OLS approach is used because population data is obtained on all variables. The more linear the more perpendicular the relationship between these variables.

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \cdots + \beta_n X_n + \varepsilon$$  \(7\)

Equation (7) is OLS regression. Where \(Y\) is variable dependent, \(\beta\) coefficients, \(X\) explanatory variable (variable independent), \(\varepsilon\) is random error.

Figure 3. Scatterplots: positive correlation, negative correlation, and 2 variabel no relationship
4. Result and Discussions

4.1. Spatial Temporal Urban Heat Island distribution

4.1.1. Land Surface Temperature from Landsat. Spatial temporal identification of surface temperature is obtained on Landsat images by recording the same/adjacent date. The criteria for image data taken are cloud <10% and taken during the daytime. The calculation results show a temporal increase in surface temperature on average by 2-5°C every 5 years. LST pattern has an increase that tends to linearly go up, with the biggest increase occurred in 2016-2019 around 5.7°C. Spatially the distribution of surface temperatures in classes 25-35°C tends to experience a significant expansion in 2016. That phenomenon it caused by significantly urban growth and sensor version of Landsat 8.

4.1.2. Urban Heat Island Value. Using equation (3), the UHI deviation value is obtained in the East Surabaya area. Until 2019, the East Surabaya area had a UHI deviation of 1.59°C compared to the surrounding area. The calculation results show there has been an increase in UHI around 0.3°C from 2001-2019. The biggest increase occurred in 2016-2019 around 0.31°C and had decreased in 2001-2006 around 0.16°C. The UHI has a tendency to change from the central direction to the east and south. The temperature in the region has increased due to changes in open space to build up area.
4.2. **Urban Form Characteristics**

4.2.1. *Urban green infrastructure.* Consists of urban green space and urban blue space. Non-build up area on the east side is dominated by ponds and mangroves. It can be observed that the higher the intensity of urban green infrastructure, the lower the intensity of surface temperature that occurs. UGI in many built areas in the form of parks and green open spaces in residential areas. While there are many trees in the industrial area and educational facilities. Vegetation in each corridor is evenly distributed.

4.2.2. *Urban geometry (UG).* Consists of sky view factor, building density, floor area ratio and mean building high. Urban geometry as a form of build-up area is identical with high surface temperature intensity. In the corridor the sky view factor is generally in the range 0.1-0.8 because the majority of the buildings still have a small geometric size. High density buildings are located in residential areas, and low building densities are located in public facilities. In the other hand, mean building high block in the area of East Surabaya ranges from 4 to 111m. Tall buildings are generally in the form of apartments, and trade in services. While the low buildings in the settlements area.

4.2.3. *Urban material (UM).* Consists of thermal admittance (surface ability to absorb heat) and albedo (surface ability to reflect heat). Areas with heat absorption and high heat expenditure are located in the industrial area.

![Figure 7](image)

**Figure 7.** (a) UHI value in 2001-2019 based on grid 500m² (b) urban form factor in East Surabaya

4.3. **Correlation between urban form and UHI**

From the stepwise results, it is determined that the most significant model with the highest R2 (R-Squared) value is the residual equation 1st. So, it can be concluded that the variables used in the regression model are building density, mean building high, sky view factor, urban green infrastructure,
urban blue infrastructure, albedo reflectance, and thermal admittance. It can be said that the omitted variable is the floor area ratio.

Table 2. Stepwise Model

| No | Spatial Autocorrelation (SA) | Adjusted R-Squared (AdjR2) | Akaike's Information Criterion (AICc) | Jarque-Bera p-value | Koenker (BP) p-value | Variance Inflation Factor (VIF) | Model |
|----|-------------------------------|-----------------------------|---------------------------------------|---------------------|----------------------|--------------------------------|-------|
| 1  | 0.000000                      | 0.292138                    | 22627.2                               | 0.0000              | 0.0000               | 2.9204                         | +BD***, +SVF***, -MBH***, +UG***, +UB***, +THERMAL***, -ALBEDO*** |
| 2  | 0.000000                      | 0.292058                    | 22629.1                               | 0.0000              | 0.0000               | 3.5475                         | +BD***, -FAR, +SVF***, -MBH***, +UG***, +UB***, +THERMAL***, -ALBEDO*** |
| 3  | 0.000000                      | 0.290379                    | 22648.00                              | 0.0000              | 0.0000               | 3.4851                         | +BD***, -FAR**, +SVF***, +UG***, +UB***, +THERMAL***, -ALBEDO*** |

Note:
- Model Variable sign (+/-)
- Model Variable significance (* = 0.10; ** = 0.05; *** = 0.01)

Next step, OLS regression results show that the lower value urban green space, urban blue space, building density, sky view factor and thermal factor the lower the UHI value. The higher albedo and mean building high value, the higher the UHI value. For this case, management urban material, urban geometry and urban green infrastructure is needed for adaptation UHI. Albedo playing important rules on UHI Spatial-Temporal Pattern with a value of -1.766193. Mean building high, building density and sky view factor became priorities urban form factor for adaptation UHI phenomenon. But for public provision, urban green space and urban blue space can be used as an option.
### Table 3. OLS Regression

| Variable              | Coefficient [a] | StdError | t-Statistic | Probability [b] | Robust_SE | Robust_t | Robust_Pr [b] | VIF [c] |
|-----------------------|-----------------|----------|-------------|-----------------|------------|-----------|---------------|---------|
| Intercept             | 32.476321       | 0.035901 | 904.618063  | 0.000000*       | 0.045098   | 720.132639 | 0.000000*     | -------- |
| BD                    | 0.006539        | 0.000439 | 14.883179   | 0.000000*       | 0.000412   | 15.851648 | 0.000000*     | 1.806550 |
| SVF                   | 0.045133        | 0.004746 | 9.509312    | 0.000000*       | 0.004885   | 9.239591  | 0.000000*     | 2.920434 |
| MBD                   | -0.024908       | 0.005064 | -4.918472   | 0.0000002       | -0.004523  | -5.057449 | 0.000000*     | 2.696343 |
| URBANGREN             | 0.008555        | 0.000455 | 18.838430   | 0.000000*       | 0.00693    | 12.342575 | 0.000000*     | 1.091063 |
| URBANBLUE             | 0.001789        | 0.000117 | 15.349501   | 0.000000*       | 0.00097    | 18.490252 | 0.000000*     | 1.113458 |
| THERMAL               | 0.000041        | 0.000005 | 8.600384    | 0.000000*       | 0.00004    | 9.334086  | 0.000000*     | 1.114171 |
| ALBEDO                | -1.766193       | 0.068463 | -25.797727  | 0.000000*       | 0.098118   | -18.00661 | 0.000000*     | 1.262938 |

Input Features: 8366  Dependent Variable: UHI  

UHI \[ Y \] = 32.476321 + (0.006539 \times \text{Building Density (BD)}) + (0.045133 \times \text{Sky View Factor (SVF)}) - (0.024908 \times \text{Mean Building High (MBH)}) + (0.008555 \times \text{Urban Green Space (UG)}) + (0.001789 \times \text{Urban Blue Space (UB)}) + (0.000041 \times \text{Thermal}) - (1.766193 \times \text{Albedo})

### 5. Conclusion

The results showed an inconsistency of UHI intensity in 2001-2019. In the processing of UHI it is necessary to consider the use of spatial-temporal data. So, that the research area can be generalized if there is a change in the distribution of UHI in a certain year. Urban form factor as an element of morphology of speech needs to be considered in this regard. Because modifying urban forms requires expensive costs, to formulate urban physical policies. Not all urban form variables affect UHI in East Surabaya. In the effort to adapt UHI urban form variables that need to be considered are urban green space, urban blue space, mean building high, building density, sky view factor, albedo and thermal. Among these alternatives, material with lower albedo is the best adaptation scenario. But, urban green infrastructure consisting of urban green space and urban blue space is the right choice to be optimized directly. As a first step, it creates thermal comfort.

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