The Impact Identification of Urban Heat Island in Coastal Urban Areas of Java Island

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Abstract. Last 20th-century urban area faced with the phenomenon of Urban Heat Island (UHI) caused over land use to meet increasing human needs. The most populous island in Indonesia is Java Island, in the year 2015 recorded population density rising 0.82% from the year 2000 to reach 20,902 people/km². The layout of urban areas in Java is bordered by sea due to the climate is more heat, such as Jakarta, Tangerang, Serang, Semarang, Surabaya, Sidoarjo, Banyuwangi and Cilacap. The phenomenon existence of UHI in 8 cities, it's interesting to be analysed using the air temperature time series throughout the 21st-century. The impact identification of UHI on a sense of discomfort and potential drought is done by correlating values of air temperature against Discomfort Index (DI) and Accumulated Potential Water Loss (APWL). Further analysis using Weather Research and Forecasting (WRF) model for last decade is done to map the spatial and temporal patterns of UHI in Java. Based on the analysis of trend line, the 8 cities experienced a temperature increase between 0.006°C/years to 0.0246°C/years, indicating the occurrence of UHI. The increase of temperature value cause the change of normal temperature value significantly every decade. The range values of the correlation between temperature and DI are 0.746 to 0.987 showed UHI effect is strong against impact sense of discomfort, but the effect is weak against a potential drought due to the range values of the correlation between temperature and APWL are −0.677 to 0.120. WRF output results showed during the last decade, UHI in spatial experience increased the area of 33°C to 34°C maximum temperature.

1. Introduction
The more years we feel a hotter air temperature, especially in urban areas. The phenomenon is called Urban Heat Island (UHI) effect. There forms a temperature difference between the cities and the surrounding suburbs because of the UHI effect [22] which causes discomfort to the city dwellers. The causes of UHI are a low amount of evapotranspiration because of less vegetation, absorption of solar radiation due to a low albedo, hindrance to the flow of air because of higher rugosity and a high amount of anthropogenic heat release [16]. The characteristic of the urban area is less vegetation and more air pollution than its surroundings.
As a consequence of the microclimate created by the UHI, the demand for energy to cool buildings increases [1]. For every 10°C temperature increase, the energy demand may go up by 2-4% in the summertime [2]. Furthermore, to meet the demand, more generation of power is needed, which results in increased amount of greenhouse gases emission and decline of climate [14]. Attenuating the effects of UHI in tropical climates is imperative and should be considered a key element in urban design to address climate change in cities [9] [10].

UHI has a negative effect in the summertime on the comfort of human health and energy consumption both at day and night [14]. The comfort level in a city can be expressed by a Discomfort Index (DI). Application of Thom’s Thermal DI could be calculated for certain places, depending on actual measurements of air temperature and relative humidity [23]. The microclimate condition of city parks in Banjarbaru city as a whole includes the category "over 50% of population feels discomfort" to "most of population suffers discomfort" [3].

Dry season months showed strong urban heat island develops preferentially on calm dry season days [7]. Besides supported by the dry season, the severity of Urban Heat Island is also supported by areas that tend to be dry climates. As per capita residential water use in Phoenix cities (856–1,514 liters or 226–400 gallons) is significantly higher compared to other U.S. cities (the daily U.S. per-capita average of 379 liters or 100 gallons) [21], widespread urban forestry that is generally applicable elsewhere would likely increase this desert city’s vulnerability to drought [12]. Drought can be identified by Accumulated Potential Water Loss (APWL) value. The causes of drought which was happened in Grobogan district was affected by APWL value [15].

One of the tropical countries is Indonesia. The most populous island in Indonesia is Java Islands with recorded population density by Statistics Indonesia (BPS) in the year 2015 reach 20,902 people/km2. The population growth is also the highest with rising 0.82% from the year 2000 to 2015 [5]. In the Java Islands consist of 6 Provinces, i.e. Banten, West Java, DKI Jakarta, Central Java, Yogyakarta and East Java. The DKI Jakarta Provinces is the most population density with has 15,328 people/km2 in the year 2015 [5]. The layout of urban areas in Java is bordered by sea due to the climate is more heat, such as Jakarta, Tangerang, Serang, Semarang, Surabaya, Sidoarjo, Banyuwangi and Cilacap.

The Urban Heat Island in the area of Terni, Italy [13] and Dhaka city, Bangladesh [6] has been simulated by using the Weather Research and Forecasting (WRF) Model. The WRF model is a mesoscale numerical weather prediction system designed to serve both operational forecasting and atmospheric research needs [20]. Ta (surface temperature) as one of the variable’s output from WRF model runs have validated by observation data from The Agency of Meteorology, Climatology, and Geophysics (BMKG) Indonesia to confirm the accuracy of the methodology [19].

The focus of this research was conducted in the coastal urban areas of Java Island. This is due to the big cities on the Java Island border the sea as a means of trading or migration using port access. In addition, the coastal area is generally hot and the big cities have a larger population. Then the vacant land is being used for housing and office needs, emissions from transportation and industry are an inevitable problem. Therefore, it is important to study in the coastal urban areas of Java Island with significant UHI potential.

2. Materials and Methods

The research period was focused on the last 20th century from January 2000 to July 2017. The location of this study was taken 8 samples of surface air observation location at BMKG Meteorological Station located in the coastal urban area of Java Island. Surface observation data taken at 8 Meteorological Station locations are monthly average temperature, average monthly moisture, and monthly rainfall amount. The Meteorological Stations are in detail can be seen in the table 1.

The initial processing is done by making the time series of the monthly average temperature data in the 8 locations. The analysis was performed using the trend line of the average monthly air temperature over time. If the trend line is positive then there is an increase in temperature, whereas if the trend line is negative then there is temperature decrease with time. The slope value in the trend line
equation indicates a trend of increase or decrease in temperature every year. The existence of UHI in these 8 locations can be identified with positive trend line shape and large slope value of temperature on equation (1).

Table 1. Location and City Population of Meteorological Station [4] [5].

| Station Name (City) | Latitude(°S) Longitude(°E) | Elevation (m) Distance of Beach (km) | Total Population (people) | Density (people/km²) | 2010 Rate (%/years) |
|---------------------|----------------------------|-------------------------------------|---------------------------|----------------------|---------------------|
| Serang (Serang)     | 6.11185                    | +100                                | 577,785                   | 2166                 | 2.67                |
| Kemayoran (Jakarta) | 6.15559                    | +4                                  | 902,973                   | 17239                | 0.31                |
| Soekarno Hatta (Tanggerang) | 6.12       | +11                                | 1,798,601                 | 11685                | 3.12                |
| Cilacap (Cilacap)   | 7.7189                     | +8                                  | 1,642,107                 | 773                  | 0.2                 |
| Tanjung Mas (Semarang) | 6.9486                | +5                                  | 1,555,984                 | 4163                 | 1.34                |
| Perak I (Surabaya)  | 110.4199                   | 0.03                                | 2,765,487                 | 7889                 | 0.62                |
| Banyuwangi (Banyuwangi) | 114.3553             | 3.0                                 | 1,556,078                 | 269                  | 2.21                |
| Juanda (Sidoarjo)   | 7.3846                     | +3                                  | 1,941,497                 | 3060                 | 0.45                |

Where:

\[ Y = a + bt \]  
(1)

Y = the projected value of the temperature variable for a selected value of \( t \) (°C).
a = the estimated value of temperature where the line crosses Y-axis when \( t = 0 \) (°C).
b = the line slope or average change in temperature for each change of 1 unit in \( t \) (°C/months).
t = time value of each month that is selected (months).

Furthermore, UHI impact analysis on the discomfort and potential of drought. Discomfort is expressed by DI [17], while the potential for drought is expressed by APWL [18]. The identification of UHI’s effect on the discomfort and potential of drought is done by correlating the time series of monthly average temperature with DI and APWL. The DI is calculated using equation 2 [17], while the APWL use equation (3) until equation (7) [18]. The classification of DI value is on table 2 [17].

Table 2. Thom’s discomfort conditions according to DI.

| Condition                                | DI  |
|------------------------------------------|-----|
| No discomfort                            | < 21|
| Under 50% of population feels discomfort | 21 – 24|
| Over 50% of population feels discomfort  | 25 – 27|
| Most of population suffers discomfort     | 28 – 29|
| Everyone feels stress                    | 30 -32|
| State of medical emergency               | >32 |
\[ DI = T - (0.55 - 0.0055RH) (T - 14.5) \] (2)

Where:
- DI = Discomfort Index.
- T = mean monthly temperature in (°C).
- RH = mean monthly relative humidity of air (%).

\[ APWL = P - PET \] (3)

If < 26.5°C:

\[ PET = 1.6 \times \left( \frac{10 \times T_{\alpha}}{l} \right)^{\alpha} x f_c \] (4)

\[ \alpha = (6.75 \times 10^{-7}) I^3 + (7.71 \times 10^{-5}) I^2 + (1.792 \times 10^{-2}) I + 0.49239 \] (5)

\[ I = \sum_{i=1}^{12} \left( \frac{T_{\alpha}}{5} \right)^{1.514} \] (6)

If > 26.5°C:

\[ PET = -0.433 T_{\alpha}^2 + 32.244 T_{\alpha} - 415.85 \] (7)

Where:
- APWL = Accumulation Potential Water Loss (mm/months).
- P = Precipitation Intensity Monthly (mm/months).
- PET = Potential Evapotranspiration Monthly (mm/months).
- \( T_{\alpha} \) = Potential Evapotranspiration (cm/months).
- I = Mean Temperature Daily (°C).
- \( f_c \) = Factor Corrected for each latitude.

![Figure 1. Research Domain on WRF Model.](image)
### Table 3. Model Configuration of WRF.

| Configuration                          | Sets                  |
|----------------------------------------|-----------------------|
| Latitude Center                        | 7.412 LS              |
| Longitude Center                       | 109.971 BT            |
| Microphysic Scheme                     | Kessler               |
| Longwave Radiation Scheme              | RRTM Scheme           |
| Shortwave Radiation Scheme             | Dudhia                |
| Surface Layer Option                   | MM5                   |
| Surface Land Option                    | NOAH Land Surface     |
| Planetary Boundary Layer Option        | YSU                   |
| Cumulus Option                         | GD Scheme             |
| Surface Input Source                   | WPS/geog              |
| SST Data Update                        | No SST Update         |

For a complete mapping of UHI effects in coastal urban areas of Java Island, WRF modeling was used over the last decade. Sampling is timed on the date of occurrence of the equinox at 12 o'clock local time. The data used is NCEP GDAS/FNL 0.25 Degree Global Tropospheric Analyses and Forecast Grids, which have the grib2 format and can be downloaded at the following link: [https://rda.ucar.edu/datasets/ds083.3/](https://rda.ucar.edu/datasets/ds083.3/). Model setting with spatial resolution: 10 and 5 km (dynamic downscaling by nesting) with the research domain as shown in Figure 1 and the model configuration as shown in table 3 [8].

### 3. Results and Discussion

#### 3.1. Identification of UHI Impact to Discomfort

The eight cities on the Java Island Coast that become the test point are urban areas. Their monthly average air temperatures from the last 20th century to July 2017 are relatively warm, ranging from 24.5° to 31.0°C. On January at the end of the 20th century, Jakarta city has a monthly average air temperature of 28.3°C which is the warmest city compared to the other 7 cities as shown in the linear trend line equations in figure 2. However, the average monthly air temperature increase in the Jakarta city is the smallest, while the highest value of 0.0041°C/month is owned by Sidoarjo city. The smallest temperature increased value of Jakarta, make the final value of the July 2017 air temperature tendency lower than Surabaya city, which is the highest and has the second highest temperature increase.

The air temperature increase also causes a sense of the air discomfort felt by the people. Based on the tested cities, all show a high positive correlation value of temperature increases and DI that range from 0.746 to 0.987. The highest positive correlation value is owned by Cilacap city, while the lowest correlation value is owned by Semarang city. The DI of the 8 cities generally shows condition of over 50% category of the population feels discomfort, although it can sometimes be at one level above or below. The highest DI occurred in November 2015 in Surabaya with a value of 27.9°C which resulted in the condition of most of the population suffers discomfort.

Trend line analysis shows that coastal cities of Java Island experienced an increase in the air temperature between 0.0005°C/months to 0.0041°C/months. This increase in temperature has an impact on the increasing discomfort sense to reach the condition of most of the population suffers discomfort. The Surabaya city which is the second highest air temperature increase, has the warmest final temperature value and the highest DI in that period. This allows Sidoarjo as the city with the highest air temperature increase in the future can surpass the final value of the air temperature trends and the highest DI of Surabaya city.
Figure 2. Relationship between Air Temperature Increase and DI in (a) Serang, (b) Tangerang, (c) Jakarta, (d) Semarang, (e) Surabaya (f) Sidoarjo (g) Cilacap (h) Banyuwangi. Y is temperature trendline equation and r is the correlation value.
Figure 3. Relationship between Air Temperature Increase and APWL in (a) Serang, (b) Tangerang, (c) Jakarta, (d) Semarang, (e) Surabaya (f) Sidoarjo (g) Cilacap (h) Banyuwangi. Y is temperature trendline equation and r is the correlation value.
3.2. Identification of UHI Impact to Discomfort

In the identification of the further temperature increase impact on drought potential, air temperature and APWL values are correlated as shown in figure 3. However, the relation of air temperature increased pattern and APWL time series pattern is less aligned than the relationship between temperature and DI. The correlation values between air temperature and APWL in these 8 cities ranged from -0.677 to +0.366. This lower correlation value is caused by more dominant rainfall factor influencing APWL value than the air temperature. The correlation values between rainfall and APWL range from 0.350 to 0.994.

The best relationship is found in Jakarta with correlation value of -0.677. This value shows the warmer air temperature then the value of APWL is smaller, so the potential for drought is indicated by the greater negative value of APWL. However in the period of January 2000 to July 2017, the highest potential drought occurred in Surabaya on October 2009 with an APWL value of -161.77 mm. Thus among the 8 cities in the period from January 2000 to July 2017, Surabaya becomes the city with the highest discomfort sense and the highest drought potential.

The low correlation values between air temperature and APWL states that the impact of temperature increase does not affect the drought potential. Drought is more potent when the low monthly rainfall values than the high average air temperature. The highest correlation value of reverse link is only owned by Jakarta. However, the greatest potential drought occurred in Surabaya, which also has the final value of the highest air temperature increase tendency surpassing Jakarta in second place.

3.3. WRF Model Output Maps of UHI

Figure 4. Surface Air Temperature Map of Java Island at 05 GMT or 12 Local Time on 2006 September Equinox (23-09-2006).
The WRF model is used to help model the air temperature changes in the Java coast as shown in figure 4. The modeling results show that the north coast of Java have a higher air temperature than the southern coast of Java. In the northern coastal region of Java, the air temperature can reach 33°C to 34°C. Meanwhile in the southern coastal region of Java, the air temperature only reaches 28°C to 30°C.

An interval of 5 years later, the model mapping results from figure 5 shows relatively similar results from the spatial temperature distribution. The temperature ranged value of both the northern and southern Java coastal regions has equal spatial air temperature distribution. However, significant changes occurred in the surface air temperatures in the Indian Ocean beside south of Java. The temperatures predominantly in the range of 20°C to 25°C in 2006 began to narrow due to the expansion of temperature values range 25°C to 28°C.

**Figure 5.** Surface Air Temperature Map of Java Island at 05 GMT or 12 Local Time on 2011 September Equinox (23-09-2011).

Significant changes seen in the next 10 years are presented in figure 6. The air temperature of both on the south coast and on the north coast has increased. The temperature reaches 28°C to 32°C on the southern coast, while on the north coast can reach 31°C to 34°C. It even observes a narrow area with air temperature of 34°C to 35°C on the border between Sidoarjo and Mojokerto city. Significant increase also occurred in the sea surface temperature of the Indian Ocean beside south of Java Island, which reaches 28°C to 31°C.

In general, the northern coastal areas of Java have a higher temperature than the southern coastal areas. The mapping of WRF model shows the change of surface air temperature during 5 year intervals of 2006 was relatively same in coastal area of Java. Significant changes of air temperature value are evident in the next 10 years in both of the northern coast, the southern coast and the
surrounding waters. Probably in the next 10 years when the occurrence of the equinox in September at 12:00 pm or 05:00 UTC, the air temperature value exceeds the range of 34°C to 35°C.

**Figure 6.** Surface Air Temperature Map of Java Island at 05 GMT or 12 Local Time on 2016 September Equinox (22-09-2016).

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