THE INTEGRATED WRF/URBAN MODELING SYSTEM AND ITS APPLICATION TO MONITORING URBAN HEAT ISLAND IN JAKARTA, INDONESIA

Laras Tursilowati1,2*, Josaphat Tetuko Sri Sumantyo1, Hiroaki Kuze1 and Erna S. Adiningsih2

1 Center for Environmental Remote Sensing (CEReS), Chiba University, Chiba, 263-8522, Japan
2 National Institute of Aeronautics and Space (LAPAN), Jl. dr. Junjunan 133, Bandung, 40173, Indonesia

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Abstract: Population growth and urbanization will impact on city development through constructions of buildings, parking lots, streets, highways and driveways. These changes lead to the Urban Heat Island (UHI), which is an important factor for future urban planning. In this context, mesoscale climate models such as the Weather Research and Forecasting (WRF) model are useful for studying the potential deficit in open green areas. The analysis of remote sensing images can provide input data indispensable to such climate model studies. In this work, we analyze the land use/land cover information inside and around the city of Jakarta, Indonesia, to study how the land use (LU) change affects UHI that is characterized by the highest surface air temperature ($T_a$) of 306 K. It is found that LU modification with the addition of 25% urban area will expand the UHI area by around 43 km² (5%). On the contrary, with the addition of 58, 95 and 440% vegetation (grassland) in the urban area, the UHI area is reduced significantly, which are 255 km² (48%), 289 km² (54%) and 466 km² (88%), respectively. This indicates that the addition of more area with open green coverage results in more reduction of UHI area. The quantitative features of this relationship will be useful for urban planners to control the UHI effects that might degrade the living conditions in this megacity.

Keywords: Urbanization; urban heat island; weather research and forecasting

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* Correspondence to: Laras Tursilowati. E-mail: laras@bdg.lapan.go.id.
INTRODUCTION

Urbanization is progressing rapidly in many Asian cities. The process of urbanization has modified the land use from the natural environment into the built environment (Maslin, 2004; Santamouris, 2006; Brauch et al., 2011). Climate change is projected to compound the pressures on natural resources and the environment, associated with rapid urbanization, industrialization and economic development (IPCC, 2007). Intensive urbanization can possibly lead to regional-scale climate change, called an Urban Heat Island (UHI) phenomenon (Santamouris, 2009).

The heat island is a reflection of the totality of microclimatic changes brought about by man-made alterations of the urban surface (Landsberg, 1981). Heat islands form in urban and suburban areas since many common construction materials absorb and retain more of the sun’s heat than natural materials in less-developed rural areas (Gartland, 2008; Bolin, 2007). Combined effects of anthropogenic heating in city centers with those of low vegetation cover and dark surfaces can enhance the heat island effect (Taha, 1997). When surface temperature is high, the latent heat transport through evaporation becomes more effective for reducing temperature as compared with the upward flux of sensible heat (Saltzman, 1983). With little or no water to evaporate, the sunlight energy goes into raising the temperature of man-made structures such as roads and buildings. After sunset, the city is so warm that it never cools down as in the countryside around it, and so the heat island effect lasts all night long. Combining the effects of anthropogenic heating in city centers with those of other factors, such as the low vegetation cover and dark surfaces can enhance the heat island effect (Rapp, 2008; Taha, 1997).

The purpose of the present study is to investigate the influence of urban canopy structure on surface air temperature inside and around Jakarta based on spatially dense meteorological observations. Urban canopy parameterization with the help of numerical model studies is implemented, including the interaction between the meteorological field and urban canopy layer (UCL). Urban surface heterogeneities are essential factors that govern the UHI (Tursilowati et al., 2009). Being the capital of Indonesia, the metropolis Jakarta is the largest city of the country, located on the northwest coast of Java island. The city area is at the mouth of the Ciliwung river that runs into the Jakarta Bay at an inlet to the Java Sea. Jakarta lies in a low, flat basin, averaging 7 m above sea level. In the northern city area, around 40% is below sea level, while the southern parts are comparatively hilly. The climate there is generally hot climate with maximum temperatures ranging from 32.7–34.0°C at noon, and minimum air temperature ranges from 23.8–25.4°C at night (DKI Jakarta provincial official portal, 2010).

In order to improve the understanding of processes that are related to neighborhood-scale climate and air quality, the UHI effects, and mesoscale circulation caused by urban-rural land cover differences, the use of mesoscale atmospheric models is increasing (Clarke et al., 2005). Here we employ the Weather Research and Forecasting (WRF) model to simulate the UHI changes in relation to the land use (LU) changes, namely the changes in the land use type. The UHI effect, in turn, can be represented by the surface air temperature (T_s) at 2 m from the ground surface in the output of WRF model runs. The approach taken in this study will be useful for the prevention and control of UHI effects in association with future city planning and urban development.

WRF simulation

The WRF model is a mesoscale numerical weather prediction system designed to serve both operational forecasting and atmospheric research needs (WRF Model Website, 2010). The model has been designed to be a flexible simulation code that is efficient in a parallel computing environment. A modular single-source code is maintained that can be configured for both research and operations. It offers a large physical selection, so it is very useful in the modeling community (Skamarock et al., 2008).

In this study, the WRF modeling system is applied to the Jakarta metropolitan areas to evaluate the influence of urban-scale surface coverage to UHI effects, based on observation in the year 2002. Here we use the Python/Delphi platform to incorporate the modification of the LU types in our urban modeling system. The Delphi programming language is an extension of the Pascal language that was designed for use in the object-oriented programming arena, called Object Pascal. Python program is part of a growing open-source software community, which includes the Linux operating system, the Perl scripting language, the Apache Web server and numerous other projects (Abolrous, 2000; Deitel et al., 2002; Pilgrim, 2004). Such an approach is considered to be very valuable for urban planners to design the city environment friendly to the residents.

DATA AND METHODOLOGY

NCEP FNL data

National Centers for Environmental Prediction (NCEP) Final (FNL) Operational Global Analysis data provide surface pressure, sea level pressure, geopotential height, temperature, sea surface temperature, soil values, ice cover, relative humidity, u- and v- winds, vertical motion, vorticity and ozone on 1.0 × 1.0 degree grids continuously at every six hours (UCAR, 2010). This product is from the Global Forecast System (GFS) that
is operationally run four times a day in near-real time at NCEP. The analyses are available at 26 mandatory (and other pressure) levels from 1000 mb to 10 mb, including the surface boundary layer and some sigma layers. Time period employed in this study is from 2 to 4 February 2008, with the benchmark of FNL data (fnl_080202_00_00–fnl_080204_00_00) in six hour time steps.

**Land use data**

A global land use/land cover (LULC) database classified according to the United States Geological Survey (USGS) LULC system is provided with WRF. In this work, the WRF model was set up by using four nests at 27, 9, 3 and 1 km horizontal grid spacing for domain 1, 2, 3 and 4, respectively (Fig. 2). Since the extent of the Jakarta metropolitan area is underpresented in the USGS dataset, we also use a more recent land cover classification for the Jakarta metropolitan region, base on the 2003 IKONOS-satellite with resolution 1 m panchromatic and 4 m multispectral (Tursilowati et al., 2009). This detailed classification result is incorporated into WRF by re-projecting the regional land cover map onto the USGS dataset using standard GIS and remote sensing using supervised classification methods. Each WRF 30-s grid cell is assigned with the land cover class with the highest fraction coverage (Tursilowati et al., 2009). This land cover data is used as the original LU (LU origin) input to the WRF Model.

**Observational data**

The three stations observational data used in this study are the air temperature data from meteorological stations operated by the Bureau of Meteorology, Climatology and Geophysics. Locations of observation data are Tanjung Priok (6°06’ S, 106°52’ E), Observatorium-Jakarta (6°10’ S, 106°49’ E) and Soekarno Hatta (6°07’S, 106°39’ E). The period data from 2 to 4 February 2008 are used, in synchronization with the time period of model runs.

**PC Cluster Specification**

The PC cluster used in this study (Fig. 1) is similar to the system described in a reference (Wang et al., 2007). The major features of our system are as follows.

1-*Server:* Dual core processor (AMD) with motherboard memory of 4112232 kB and SATA 300 GB hard disk, operated by Linux OS 5 (Redhat Enterprise).

2-*Node clusters:* 15 node clusters, with each node having dual core processor (AMD1211), SATA Raid, DDR2 20597884 kB, and 500 GB HDD, operated by Linux OS 5.

3-*Softwares:* Redhat Linux 5, Advance Research WRF Version 3 (AR-WRF V3), Fortran 90 Compiler, Grids Analysis Display System (GrADS), NetCDF, HDF4, Matlab, Vis5D, MPICH2 (PGI+GCC), Apache, Php and MySQL.

**Domain configuration**

The domain configuration used in the WRF model calculation is shown in Table 1. This configuration is basically the same as the one described in literatures (Wang et al., 2007; UCAR, 2010).

Figure 2 shows the nesting of four regions used for running the model, namely the first (widest) nesting with the area of 1°23’–10°16’ S, 100°44’–118°33’ E (western Indonesia), the second one with 3°40’–8°27’ S, 103°02’–111°26’ E (Java and southern Sumatera), the
Table 1. The domain configuration in the WRF model

<table>
<thead>
<tr>
<th>Field</th>
<th>Domain 1</th>
<th>Domain 2</th>
<th>Domain 3</th>
<th>Domain 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Meridional Grid Dimension</td>
<td>73</td>
<td>100</td>
<td>121</td>
<td>100</td>
</tr>
<tr>
<td>Zonal Grid Dimensions</td>
<td>40</td>
<td>64</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>Vertical Level Grid Resolution</td>
<td>31</td>
<td>31</td>
<td>31</td>
<td>31</td>
</tr>
<tr>
<td>Terrain Resolution</td>
<td>27 km</td>
<td>9 km</td>
<td>3 km</td>
<td>1 km</td>
</tr>
<tr>
<td>Explicit Moisture Scheme</td>
<td>WRF</td>
<td>WRF</td>
<td>Purdue</td>
<td>No</td>
</tr>
<tr>
<td>Longwave Radiation Scheme</td>
<td>RRTM</td>
<td>RRTM</td>
<td>RRTM</td>
<td>RRTM</td>
</tr>
<tr>
<td>Shortwave Radiation Scheme</td>
<td>Dhudia</td>
<td>Dhudia</td>
<td>Dhudia</td>
<td>Dhudia</td>
</tr>
<tr>
<td>Surface Layer</td>
<td>MM5</td>
<td>MM5</td>
<td>MM5</td>
<td>MM5</td>
</tr>
<tr>
<td>Land Surface Physics</td>
<td>5-layer</td>
<td>5-layer</td>
<td>5-layer</td>
<td>5-layer</td>
</tr>
<tr>
<td>Cumulus Scheme</td>
<td>Betts-Miller-Janjic</td>
<td>Betts-Miller-Janjic</td>
<td>Kain-Fritsch</td>
<td>No cumulus</td>
</tr>
<tr>
<td>PBL Type</td>
<td>YSU scheme</td>
<td>YSU scheme</td>
<td>YSU scheme</td>
<td>YSU scheme</td>
</tr>
</tbody>
</table>

*: SM=Single Moment, RRTM=Rapid Radiative Transfer Model, MM5=Mesoscale Model5, YSU=Yonsei University

Land use modification

In the model run, hypothetical modification of LU is implemented in accordance with the following four scenarios: (s1) modification of all the grassland into urban type (reducing 100% grassland), (s2) modification by added 48% of grassland (s3) added 95% grassland, and (s4) added 440% grassland. The open-source programs of Delphi/Python are used to modify the LU type. In (s1), Delphi program modifies all of grassland area into urban area: in terms of the USGS standard numbering of land use index, this corresponds to the change from index 7 to index 1, whereas Python program is used to modify the LU by adding the land use type per grid manually (s2–s4).

Parameterization of longwave radiation balance, anthropogenic heat flux and heat storage

The sky-view factor is a dimensionless parameter between 0 and 1, representing the fraction of visible sky at a reference site in comparison with the sky fraction over a flat horizontal surface without view obstruction (Clarke et al., 2005). The sky-view factor for a road of an infinitely long urban canyon is calculated as a function of the road width \( w \) (m) and the building height. The assumption of infinitely long urban canyons can be justified because of the grid structure of roads and the housing density in the suburban developments of Jakarta. The sky-view factor is introduced to the longwave radiation balance \( R_{long} \) (Wm\(^{-2}\)) of the urban land cover categories in the WRF slab model (Dudhia, 1993).

Numerical design

The nesting simulations are conducted for the original (unmodified) LU and four LU use modifications (s1–s4) using the four horizontal domains. The overall scheme of the methodology is shown in Fig. 3.

RESULTS AND DISCUSSION

Land use modification

Different LU distribution data are used as input data to the WRF model runs. The original LU map in and around Jakarta (5°20’–6°25’ S, 106°30’–107°12’ E) is shown in Fig. 4.
The legend indicates the LU index taken from the USGS standard categories (see Table 2). As seen from Fig. 4, the LU distribution consists of 10 types, namely, (LU index 1) urban, (2) dryland cropland/pasture, (3) irrigation cropland/pasture, (5) cropland/grassland mosaic, (7) grassland, (8) shrubland, (16) waterbody, (17) herbaceous wetland, and (19) barren/sparse vegetation. Among these, dominant LU types in Jakarta are (1) urban, (3) irrigation cropland/pasture, and (16) waterbodies including the ocean in the northern part. The urban area is concentrated in the central part of the study area shown in Fig. 4. Moderately found categories are (2) dryland cropland/pasture, (5) cropland/grassland mosaic, and (7) grassland.

Figure 5 represents the result of LU modification according to (s1), in which all the grassland has been changed into urban. Figure 6 shows the result of LU modification from the original LU using the (s2) to (s4), with the change from urban to grassland with a fraction of around 58% (s2) (a), 95% (s3) (b), and 440% (s4) (c).

### Table 2. Land use index of USGS categories

<table>
<thead>
<tr>
<th>LU Index</th>
<th>Description</th>
<th>LU Type</th>
<th>Description</th>
<th>LU Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Urban</td>
<td>13</td>
<td>Evergrn. Broadlf.</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Dryland Crop</td>
<td>14</td>
<td>Evergrn. Needlf</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Irrg. Crop. Past.</td>
<td>15</td>
<td>Mixed Forest</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Mix. Dry/Irrg.C.P.</td>
<td>16</td>
<td>Water Bodies</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Crop./Grs. Mosaic</td>
<td>17</td>
<td>Herb. Wetland</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>Crop./Wood Mosc</td>
<td>18</td>
<td>Wooded wetland</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>Grassland</td>
<td>19</td>
<td>Bar. Sparse Veg.</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>Shrubland</td>
<td>20</td>
<td>Herb. Tundra</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>Mix Shrb./Grs.</td>
<td>21</td>
<td>Wooden Tundra</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>Savanna</td>
<td>22</td>
<td>Mixed Tundra</td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>Decids. Broadlf.</td>
<td>23</td>
<td>Bare Gmd. Tundra</td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>Decids. Needlf.</td>
<td>24</td>
<td>Snow or Ice</td>
<td></td>
</tr>
</tbody>
</table>

Fig. 4 Original (unmodified) land use.

Fig. 5 Land use modification resulting from s1 (grassland is modified to urban: LU index change of 7 to 1).

Fig. 6. Land use modification by changing a fraction of urban area into grassland: (a) 58% (s2), (b) 95% (s3) and (c) 440% (s4).
The statistics of LU before (LU origin) and after modification is shown in Fig. 7. It is noted that the categories of dryland/cropland and pasture (index 2), cropland/greenland mosaic (index 5), and waterbodies (index 16) are unchanged in all the scenarios, whereas those of urban (index 1), irrigation cropland/pasture (index 3), and grassland (index 7) has been changed.

Figure 8, on the other hand, shows the land area that has been changed as compared to the original distribution. The fractional changes are summarized in Table 3. By reducing 100% grassland, the urban area increased to 339 km² (from 1360 to 1699 km²). With the addition around 58, 95 and 440% grassland, then the urban area was reduced 185 km² from origin (±14%), 309 km² (±23%) and 835 km² (±61%), respectively (Table 3).

Urban Heat Island

The distributions of $T_a$ obtained from the WRF model calculations are shown in Fig. 9 (spatially) and statistically shown by Figs 10–11 and Table 4. All the panels shown in Fig. 9 are from WRF model runs at a time step corresponding to around 11:00 a.m. local time.

The $T_a$ obtained with the original LU is shown in Fig. 9a. As seen in this figure, the pattern of UHI is concentrated in urban areas with $T_a$ about 306 K (red color), while the surrounding area having the LU of a mixture of dry land, rice paddies, and irrigation shows a lower $T_a$. Fig. 9b (s1) shows the spread of UHI area by approximately 43 km² (5%) with the addition of 25% urban (i.e., reduction of 100% grassland). Thus, it can be confirmed that the UHI occurs in the central city. The influence of including more vegetation area, on the other hand, can be seen from Figs 9c–e. In Fig. 9c (s2) the UHI area characterized with $T_a$ 306 K decreases by approximately 48% (255 km²) when 58% of grassland added. In Fig. 9d (s3) the UHI decreases by approximately 54% (289 km²) with the addition of 95% grassland, while Fig. 9e (s4) shows the reduction of approximately 88% (466 km²) with the addition of 440% grassland. Especially in Fig. 9e, it is seen that the distribution of the highest $T_a$ appears in the very limited region. This is due to the addition of a wide spread of grassland, around 440%. Figure 11 shows the changes of area distributions in accordance with $T_a$ ranges after the LU modification.

![Fig. 7 Graphs of land use (origin and after modification) (km²) as input for WRF model runs.](image1)

![Fig. 8 The changes of LU before and after modification (km²).](image2)

![Fig. 10 Distributions of $T_a$ from the results of WRF model runs.](image3)

### Table 3. Fractional changes from the original LU

<table>
<thead>
<tr>
<th>Land Use Types</th>
<th>scenario 1</th>
<th>scenario 2</th>
<th>scenario 3</th>
<th>scenario 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Urban</td>
<td>25%</td>
<td>-14%</td>
<td>-23%</td>
<td>-61%</td>
</tr>
<tr>
<td>Dryland</td>
<td>-2%</td>
<td>0%</td>
<td>1%</td>
<td>2%</td>
</tr>
<tr>
<td>Crop P.</td>
<td>-1%</td>
<td>0%</td>
<td>0%</td>
<td>-39%</td>
</tr>
<tr>
<td>Irrg. Crop.</td>
<td>-1%</td>
<td>0%</td>
<td>1%</td>
<td>6%</td>
</tr>
<tr>
<td>Past.</td>
<td>-1%</td>
<td>0%</td>
<td>1%</td>
<td>6%</td>
</tr>
<tr>
<td>Crop./Grs. Mos.</td>
<td>-1%</td>
<td>0%</td>
<td>1%</td>
<td>6%</td>
</tr>
<tr>
<td>Waterbody</td>
<td>-100%</td>
<td>58%</td>
<td>95%</td>
<td>440%</td>
</tr>
</tbody>
</table>
Fig. 9 $T_s$ (K) from WRF runs with input (a) LU origin, (b) LU index 7 to 1, (c) +58%, (d) +95% and (e) +440% grassland.
Model Validation

$T_a$ as one of the variable’s output from WRF model runs (using LU origin as input) have validated by observation data from The Agency of Meteorology, Climatology and Geophysic (BMKG) Indonesia to confirm the accuracy of our methodology. Locations of observation data are Tanjung Priok (6°06'S, 106°52'E), Observatorium-Jakarta (6°10'S, 106°49'E) and Soekarno Hatta (6°07'S, 106°39'E). The result of model validation is shown in Fig. 12.

The range of R-squared value ($R^2$) $T_a$ WRF model runs compare an observation data as the reliability value between 0.499–0.641 (Fig. 12). This represents the strong correlation (Ott & Longnecker, 2001; Pallant, 2007). Validation of model runs with observation data shows WRF model is good enough to represent the actual climate conditions ($T_a$).

CONCLUSIONS AND FUTURE WORKS

The analysis of the land use (LU) change affects the Urban Heat Island (UHI) inside and around Jakarta city as the capital of Indonesia using the Weather Research and Forecasting (WRF) has been studied. The LU modification using Delphi and Python program have applied to investigate UHI spreading. UHI characterized by highest surface air temperature ($T_a$) of 306 K. The spatial and graphical analysis shows significant differences. LU modification of grassland into urban area will expand the area of UHI around 43 km$^2$ (5%).

The results of this study can still be developed by modification of land use by changing the other land use type, so that the results of running the model will be analyzed further for the sake of a better city planning. The future work is to analyze the other climate variables (i.e. albedo, latent heat flux, planetary boundary layer height, accumulated total precipitation cumulus, etc.).
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REFERENCES


