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RESEARCH PAPER

A Mesoscale Meteorological Model of Modified Land Cover to the Effect of Urban Heat Island in Jakarta, Indonesia

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Abstract - A mesoscale meteorological model of modified land cover to the effect of urban heat island (UHI) in Jakarta was done. Although higher temperature in the city has been generally known, factors and issues that result in the increase of temperature particularly nighttime temperature over the city, however, are not well-understood. Jakarta, the capital of Indonesia, is encountering urbanization problems foremost. The increasing demand of housing as well as rapid development of sky crapper building, market places and highway diminishes the vegetation which in turn trap heat in the troposphere throughout the year, particularly during dry season on June-August. The fifth-generation mesoscale meteorological model (MM5) was employed in the study. The model involves medium range forecast planetary boundary layer (MRF PBL) scheme and land surface with two following parameters: i.e. roughness length over land and thermal inertia of land. These two parameters are chosen to enhance the characteristics of land surface. The simulation was carried out for 3 days on August 5-7, 2004 during dry season. The results showed that the simulation of surface temperature done by MM5 modified land cover described a good comparison to that of weather observation data. As a result, the effect of UHI was also well-observed during day-time. In addition, MM5 modified land cover simulation also illustrated a well-development of sea-breeze and country-breeze during mid-day and nighttime, respectively. However, long-term simulation is still required. Thus, daily diurnal cycles of air temperature and their differences can be well-observed in detail.

Keywords: MM5, MRF PBL, urban heat island, dry season, sea-breeze

Introduction

Urban heat island (UHI) is a recent field of study to investigate the diurnal cycles of temperature over the city and its surrounding areas. In fact, the reason for the increasing of air temperature over the city is due to the industrial activities, anthropogenic emission and urban development foremost. Rizwan *et al.* (2008) studied the development of UHI and found that urbanization and anthropogenic heat were among factors that trigger UHI. During daytime, since less vegetation and water bodies existed in the city, it therefore contributes to less evaporation occurred over the city. The incoming short wave radiation is transmitted over such urban land cover as: city building and other built-up land e.g. terraces, highway and fly-over bridges. The reflection in terms of outgoing long wave radiation as well as polluted air lead to the rise of the potential greenhouse effect and eventually increase the daytime city temperature. Meanwhile during nighttime, the vast amounts of heat stored in the urban structures are slowly released into the air and keep the city warm throughout the night. On the other hand, in the rural areas where irrigated cropland, grassland and traditional building take place, as surface grounds cool rapidly, it tends to decrease the air temperature and cooler temperature arose in a whole night. Consequently, a significant nighttime temperature differences observed both in the city and the rural areas lead to the effect of UHI. In fact, this warm nighttime city temperature may affect its surrounding areas, and enlarge local temperature in particular suburb areas.

Jakarta is the capital and the largest city in Indonesia. Geographically, it is situated at 6.12 ^{o}S and 106.65 ^{o}E in the Southeast Asia. Jakarta like many other cities located in the equatorial region has a hot and humid tropical climate (Ahrens, 2007). In recent times, Jakarta, a centre for government administration, business and economics matters, is encountering the rapid urbanization difficulties foremost. The increasing demand of housing as well as rapid development of sky crapper building, market places and highway is diminishing the vegetation. The industrial district located in the west as well as household demand of energy and electricity, high intensity of vehicles and severe traffic jams occur in the city which, in turn, contributes to the rise of heat trapped in the troposphere all over the year, particularly during dry season (June-August).

Nevertheless, a distinctive description of diurnal cycles of temperature in Jakarta is still poorly understood. Therefore, an intensive study of diurnal cycles of temperature that drive UHI effect is required to be conducted over Jakarta city and its surrounding areas. Furthermore, temperature differences developed in the urban, suburb, rural areas and the sea drive the formation of local wind circulation, i.e. sea-breeze during daytime and land-breeze also country breeze during nighttime as a result of the temperature variability of these rural areas neighboring the city. A particular effort has been conducted to investigate the temperature differences over inland and sea and its further implication to the sea-breeze circulation over Jakarta city as studied by Sofyan *et al.* (2005) using mesoscale meteorological model (MM5). Similar research was also carried out by Hu *et al.* (2005) in China.

On the other hand, several researches have been carried out to study urban modification by using MM5. For example, Grossman-Clarke *et al.* (2005; 2007) have studied urban modification and its near-surface variables effect in a semi-arid region by using MM5 model, and Lo *et al.* (2005; 2007) examined the influence of land use change to the development of sea-breeze and diurnal cycles of temperature in Hongkong. Therefore, the objective of the present study was to investigate the effect of land cover implication to the development of UHI over Jakarta and its outlying areas by using MM5. The model was also utilized to describe UHI effect to the following physical meteorology, i.e. development of sea-breeze and country-breeze circulation, and apparent temperature in the city.

Materials and Methods

Design of numerical experiment

The research was conducted by introducing the Fifth-Generation Pennsylvania State University-National Center for Atmospheric Research Mesoscale Model (MM5). MM5 is a non-hydrostatic model, σ pressure coordinate that the terrain profile is employed to the model. There are 4 domains that present the outermost and the innermost of Jakarta as shown in Figure 1, 31x31 horizontal grids are utilized to all domains in the model. The innermost domains relating to domain 1 and 2 span Jakarta city and Bogor, a rural district where agricultural region is situated in the south also Tangerang and Bekasi representing the suburb areas are located in the northwest and the southeast, respectively. Furthermore, Δx=Δy=9 km and 9 km are applied to domain 3 and 4, respectively. Moreover, the outermost domains illustrating domain 1 and 2 with Δx=Δy=9 km cover almost an entire region of West Java and the southwestern part of the Java Sea. In addition, 35 pressure levels ranging from 1000-100 hPa including 15 vertical levels with fine resolution to the earth's surface were employed to the model.

In addition to horizontal and vertical grids, the model is also supported by following physical parameters: (a) Medium range forecast planetary boundary layer (MRF PBL) scheme. This scheme was chosen to conduct a better computation of surface heat fluxes. MRF PBL scheme was also employed in MM5 study carried out by Durante *et al.* (2006), Deng *et al.* (2006), and Ruiz-Arias *et al.* (2008), (b) Grell cumulus scheme was included in domain 1 and 2, (c) Cloud atmospheric radiation. Whereas the following initial boundary condition were implemented in the model: (a) 30 sec. (0.925 km) USGS terrain height data, (b) 30 sec. (0.925 km) Global 24-category USGS land use/cover data, (c) the modification of 30 sec. (0.925 km) Global 24-category USGS land use/cover data, (d) 0.5° x 0.5° resolution of ECMWF data.

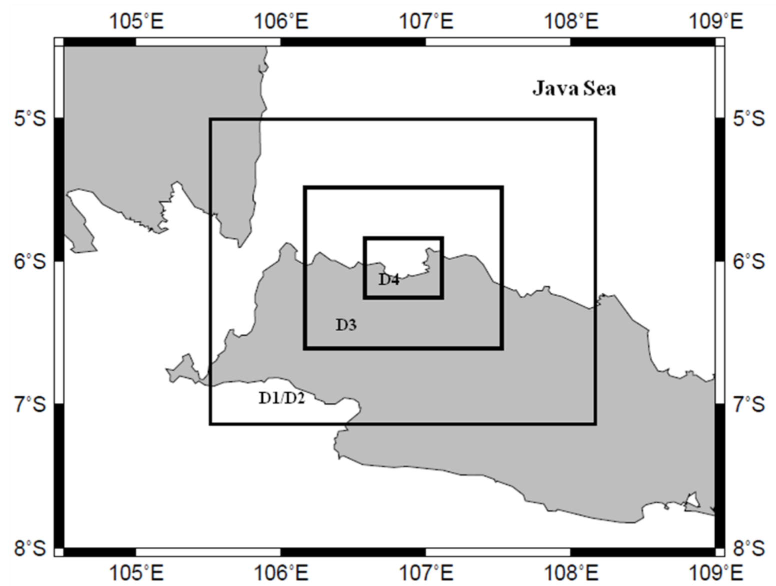

Figure 1. Domains of MM5 simulation.

Land cover data

As described in the numerical set-up above, USGS 24-category of land use/cover (hereafter refer to the standard-release land cover data) was implemented to the model. Yet, the data is under-represented due to less urban areas captured in Jakarta city as drawn in Figure 2a. Inaccurate standard-release land cover data have also been identified by a number of studies (e.g., Brazel *et al.*, 2003; Grossman-Clarke *et al.*, 2005; 2007). They initiated to improve the standard release land use data prior to run the model. The inaccurateness of the standard release land use data might result in either lack adaptation of the USGS-24 category land use/cover to the recently revised MM5 model or an outdated USGS-24 category land use/cover employed in the MM5 model since the data were produced in 1976. In Figure 2a, it is obviously shown that land cover in central Jakarta is typically dominated by cropland/grassland mosaic meanwhile those in the west and the east are characterized by irrigated cropland and pasture and a small amount of urban areas is centrally situated in the southeast. It seems that the land cover resembles the condition of Jakarta in 1960s.

Hence, the standard-release land cover data is required to be modified by extending the growth of urban area in Jakarta. Furthermore, based on the geographical information provided by the Google Earth engaged with the standard-release land cover information. Thus, the following scenarios are approximately designated to modify the standard-release land cover data. (a) to replace the cropland/woodland mosaic into urban and built-up land, (b) to replace the irrigated cropland and pasture dominating in the coastal area into wooded wetland and sparsely vegetated in a certain crowd urban area reflecting the city park and bare ground in central Jakarta and city outskirts, respectively.

Therefore, the actual urban and other land cover information in Jakarta can be well-approached. As a result, domain 4 in the model has been thoroughly changed by adjusting urban areas in almost a whole surface topography as shown in the figure 2b. In the meantime, an improved land cover has also been adapted to the domain 2 and 3. Figure 2b shows the recent urban growth in Jakarta city where urban built-up is dominantly distributed in the domain. Since the land cover has been changed, it must have also been changed their land properties, i.e. albedo, soil moisture, thermal and surface roughness. Therefore, both standard-release and modified land cover need to be tested. The strategies to do so are (a) running the MM5 model with standard-release land cover data, (b) implementing this modified land cover version of Jakarta and its surrounding areas to the initial boundary condition and re-running the MM5 model, (c) plotting and evaluating the appropriate results of these two models and to verify with field observation data recorded in a certain weather station, (d) designating the model need to be used for additional investigation of sea-breeze and surface heat budget. The simulation was carried out for 5 days on August 4-8, 2004 during dry season. The season was selected to see how high the diurnal variations of temperatures in this period where less precipitation occurred in this season. Short time of simulation for 3 days during dry season was also performed by Chang *et al.* (2010).

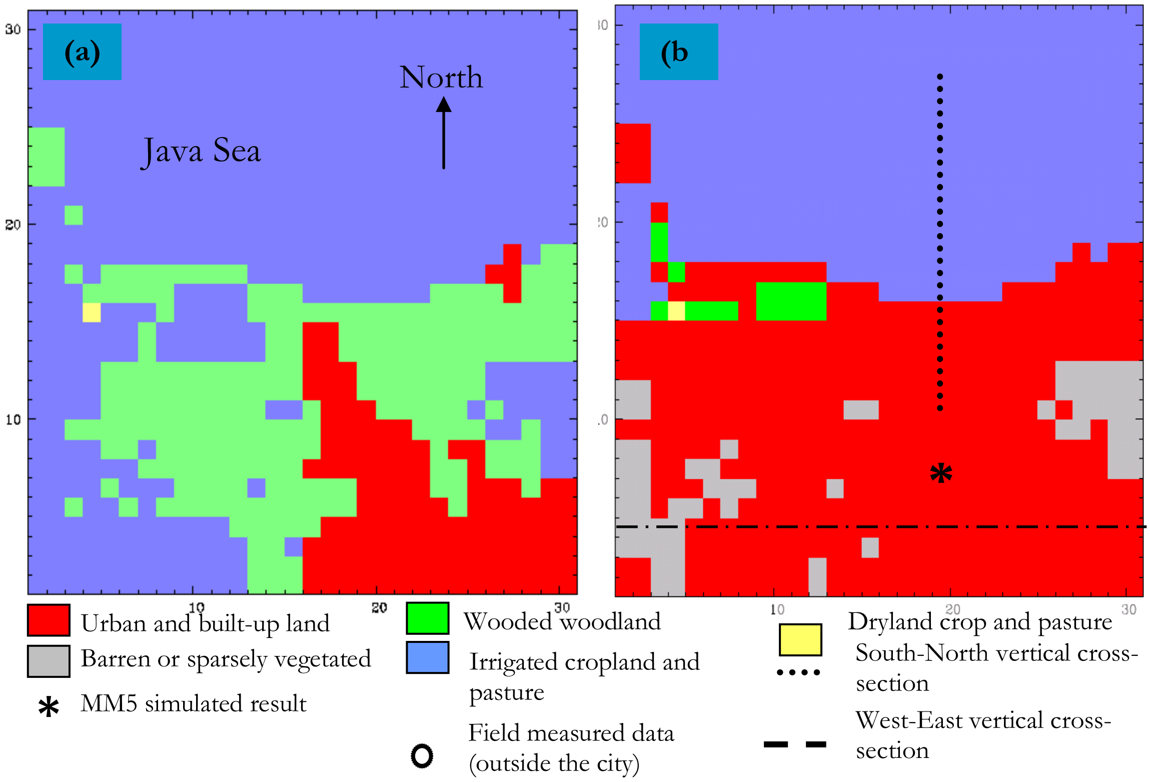

Figure 2. The MM5 land cover model of domain 4 for a) the standard-release of USGS-24 category land cover and b) modified version.

Results and Discussion

Simulated and observed daily cycles of temperature and wind

Figure 3 shows the temperature plotted at surface level (990 hPa) with different strategies of simulation and their verification to the measured weather data originated from NOAA historical weather data archives. It is shown that both MM5 standard-release and modified land cover model are not well-coincided with the observation data. The measured weather data on August 6, 2004 shows higher temperature occurred during daytime. Chang *et al.* (2010) also showed the differences of time series comparison of temperature during dry season between observation data and modified land cover. Meanwhile, temperature range between Jakarta and Klang Valley region as studied by Chang *et al.* (2010) showed the similar pattern with maximum temperature reach 306K in the afternoon and minimum temperature of 296K in the morning. Both conditions reflect the typical equatorial climate during dry season. However, the present study showed the similar result with another study by Sofyan *et al.* (2005).

The maximum temperature differences of 6.4K are found at 11.00 and 12.00 local standard time (LST) in the afternoon (Figure 3). These deviations are caused by certain meteorological conditions occurred in the weather station which are not precisely interpreted in the MM5 model e.g. warm advection, surface heating and free convection due to cloud formation or is it located in a region of subsidence inversion?. Furthermore, these physical processes need to be adapted to the MM5 model. In fact, weather station is located in the international airport which is 80 km west of Jakarta around suburb area where heavily industrialized areas are also concentrated there. Thus, it may result in high temperature measured in the station. Yet, the recorded surface temperature of 306K on August 6, 2004 typically reflects the actual daytime temperature in suburb area of Jakarta.

Figure 4 shows the simulated surface temperature of MM5 modified land cover model in Jakarta city, the sea, western and eastern rural areas. Domain 3 is used to plot the diurnal variation of simulated results of the west and rural areas meanwhile domain 4 is used to plot the city and the sea diurnal variation of simulated results. Furthermore, western rural area located 110 km southwest of Jakarta city is characterized as land cover of irrigated cropland and pasture, and so does eastern rural area. The precise locations of these rural and other places are shown in figure 5. It is shown that during daytime, temperature was higher in the city instead of in the sea and both rural areas (Figure 4 and Figure 5). The maximum temperature of 302.5K was observed in the afternoon. Meanwhile, during nighttime, the effect of UHI was apparently developed (Figure 5). The effect might have caused the west rural area temperature to increase, this came into question why?. It is shown that on August 6, 2004, the temperature in this west region remained constant in early evening, rose at midnight and decreased rapidly in late evening. It can be explained that in early evening, the temperature is largely influenced by city temperature. The temperature is distributed over this region due to thermal city expansion. Since heavy factories, international airport and heavy traffics are also concentrated there, it then contributes to intensify the local temperature and reaches the maximum temperature of 297.2K at 23.00 LST (Figure 5) where the urban heat effect is strong in this region. Meanwhile, sea-surface temperature is lower in the afternoon and higher at night. The former will be further highlighted in surface energy balance discussion. In addition, temperature differences between the city and western and eastern rural areas are 2 K and 1.75 K, respectively. The similar differences was also showed by Lo *et al.* (2007) that described urban areas in Hongkong are 2-4˚C warmer than rural areas and UHI occurred during day and nighttime.

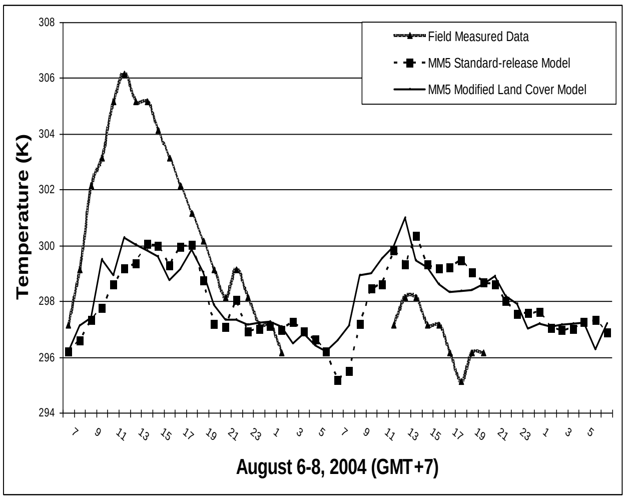

Figure 3. The simulated surface temperature (K) of the MM5 standard-release, modified land cover model and the measured surface temperature (K) from the weather station.

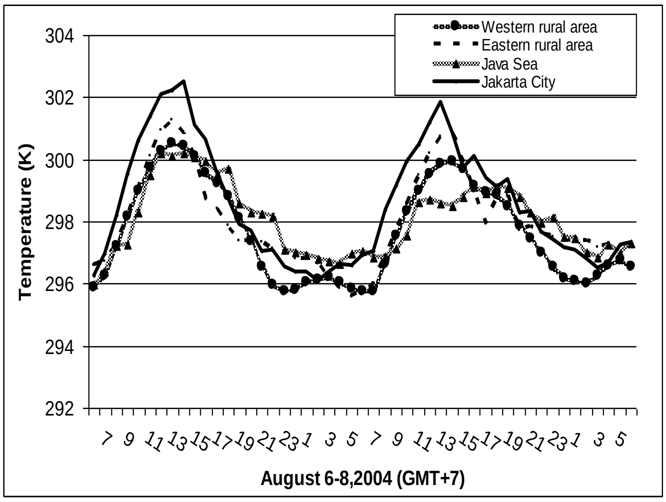

Figure 4. The MM5 modified land cover model for simulated surface temperature (K) in Jakarta city and its surrounding areas.

Nevertheless, small diurnal range of temperature of 4 K is found in the Jakarta and its surrounding areas. It can be stated that Jakarta is stretched in the coastal area where water cycles over the city are largely influenced by the sea. The variability of temperature also depends on land properties of moisture availability. Grossman-Clarke *et al.* (2005) stated that low values of moisture availability may lead to the increase of surface air temperature.

Simulated heat index apparent temperature

Figure 7 shows the simulated heat index of MM5 modified land cover model in central Jakarta during dry season. Heat index is relating to the actual temperature associated with the relative humidity to determine the apparent temperature felt by the human body. The heat index is calculated according to Zunis Foundation (2008):

$$HI=16.923+((1.85212*10^{-1})T)+(5.37941*R*H)-((1.00254*10^{-1})T*RH)+((9.41695*10^{-3})*T^{2})+((7.28898*10^{-3})*RH^{2})+((3.45372*10^{-4})*T^{2}*RH)$$

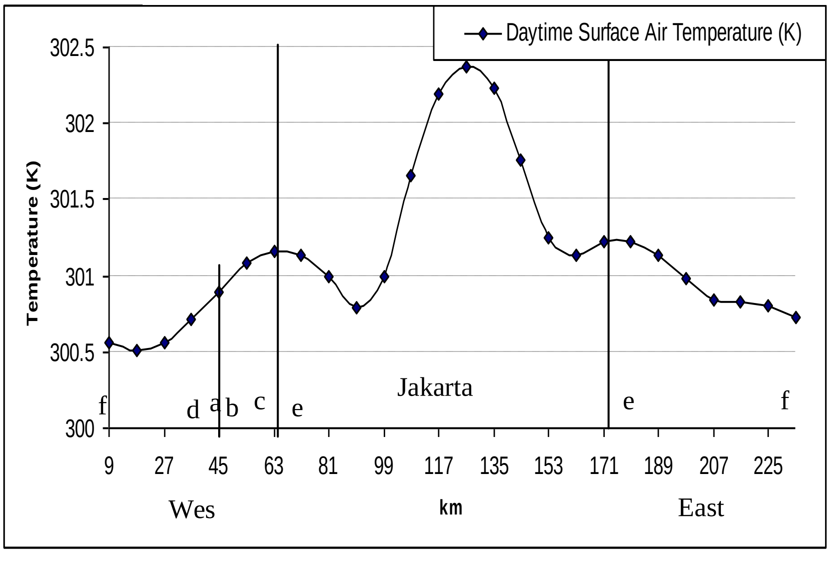

Figure 5. The MM5 modified land cover model of domain 3 for west-east vertical cross-section of simulated surface temperature (K) at 15.00 LST on August 6, 2004, a) weather station, b) international airport, c) heavy factories, d) trans-Sumatra highway, e) suburb areas, f) rural areas.

$$-((8.14971*10^{-4})*T*RH^{2})+((1.02102*10^{-5})*T^{2}*RH^{2})-((3.8646*10^{-5})*T^{3})$$
$$+((2.91583*10^{-5})*RH^{3})+((1.42721*10^{-6})*T^{3}*RH)$$
$$+((1.97483*10^{-7})*T*RH^{3})-((2.18429*10^{-8})*T^{3}*RH^{2})$$
$$+((8.43296*10^{-10})*T^{2}*RH^{3})-((4.81975*10^{-11})*T^{3}*RH^{3})(1)$$

Where H = relative humidity (%).
T = actual temperature (K).
The eq. (1) is frequently applied for T > 249.15K.

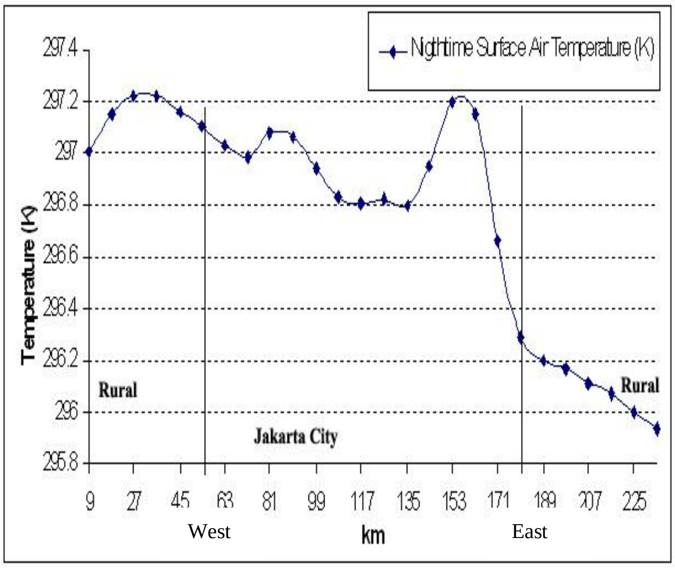

Figure 6. The MM5 modified land cover model of domain 3 for west-east vertical cross-section of simulated surface temperature (K) at 23.00 LST on August 6, 2004.

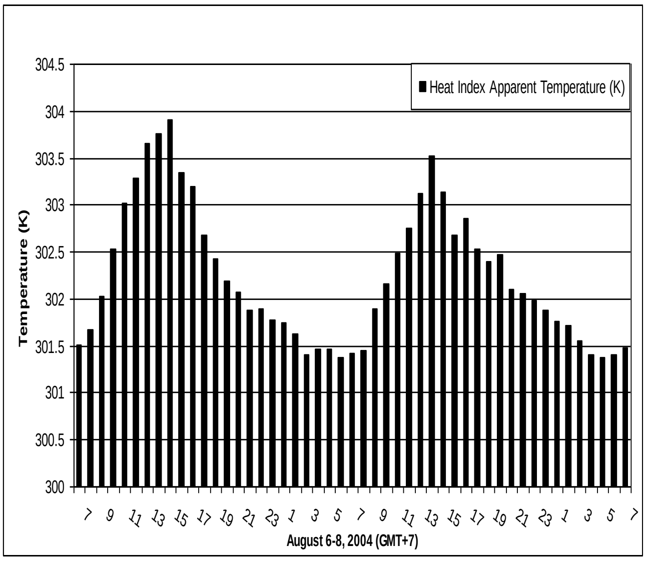

Figure 7. The MM5 modified land cover model of domain 4 for calculated heat index apparent temperature (K) in central Jakarta.

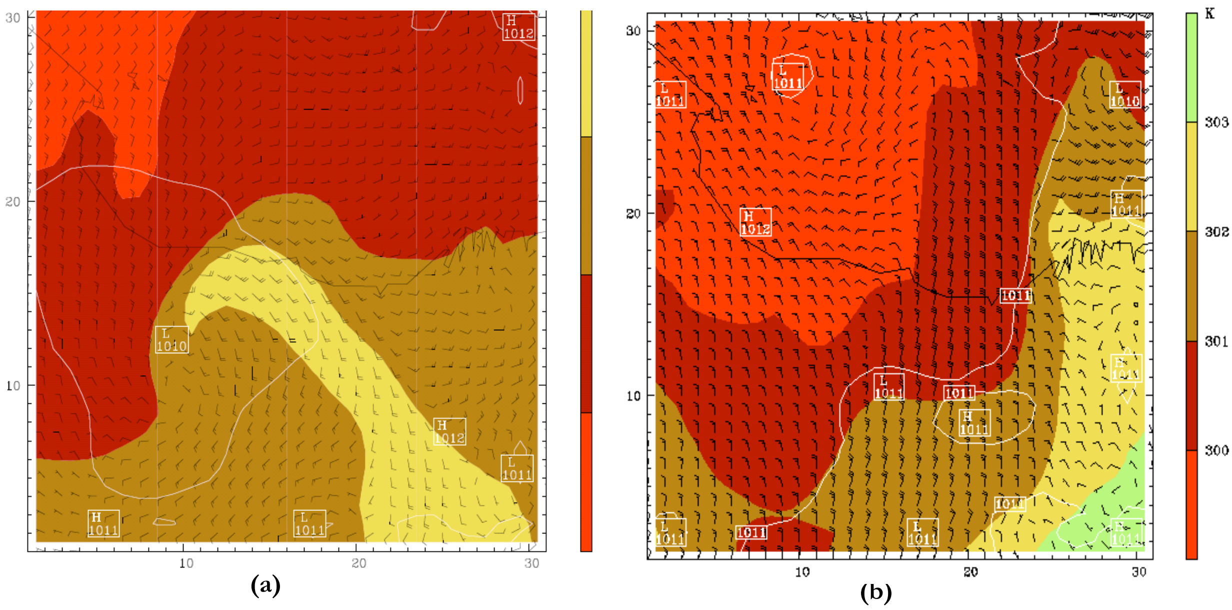

Figure 8. The domain 4 of simulated surface wind (ms^{-1}) and potential temperature (K) for a) MM5 standard-release model and b) modified land cover model in Jakarta city at 15.00 LST on August 8, 2004.

Simulated surface wind field

Figure 8 shows the simulated surface wind field for both MM5 standard-release model and modified land cover model. The two models show a reasonable result since high and low pressure was well-developed over land and sea during daytime due to temperature differences and further driving the sea-breeze circulation over Jakarta. It is shown that in both models, the easterly wind was developed over land and sea, and stronger wind occurred over the sea. However, the differences between these two models result are obviously shown in MM5 modified land cover model (Figure 8b). As a result of urban-induced expansion, the land temperature was higher than that of MM5 default model. Thus, the temperature may develop a low surface pressure and lead to the formation of surface convergence over central Jakarta. Because of pressure gradient, it then contributes to a strong development of the sea-breeze. Figure 8b showed the surface convergence zone in central Jakarta where surface potential temperature reach 304 K and stronger wind move inward to the center of low-pressure area. Hence, the MM5 modified land cover model was then used to analyze the vertical circulation of the sea-breeze and the country-breeze developed during day and nighttime over Jakarta city, respectively.

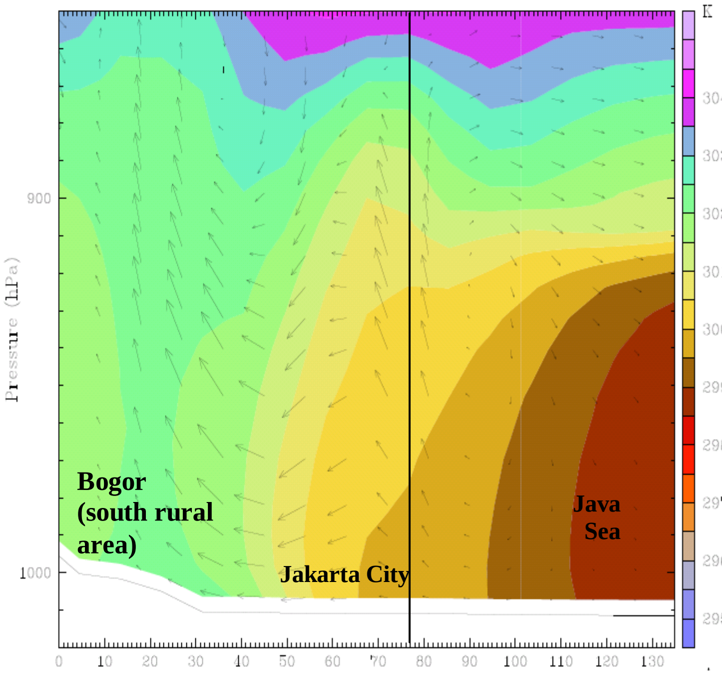

Figure 9. The MM5 modified land cover model of domain 2 for south-north vertical cross-section of simulated wind and potential temperature (K) at 15.00 LST on August 8, 2004.

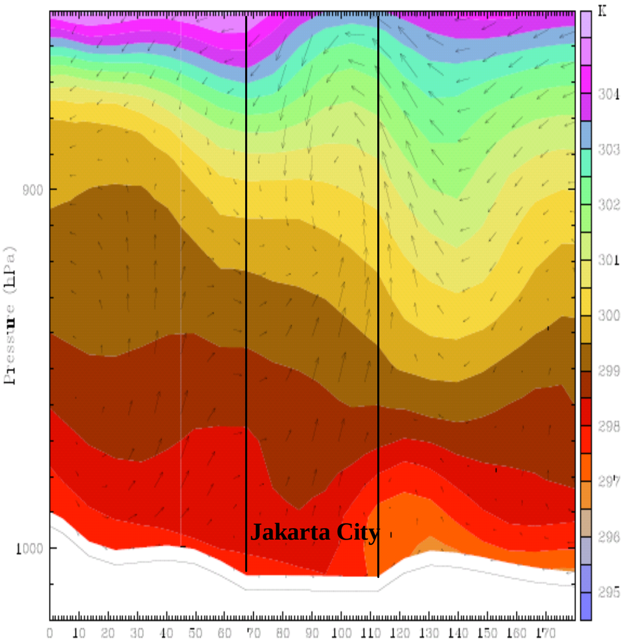

Figure 10. The MM5 modified land cover model of domain 2 for west-east vertical cross-section of simulated wind and potential temperature (K) at 1.00 LST on August 8, 2004.

Simulated sea-breeze and country breeze

As shown in figure 8b, high and low surface pressure tendency is formed during daytime over the sea and land, respectively. Hence, it drives the surface wind to flow and to accelerate the speed while going through the land as shown in Figure 9. Thus, stronger wind with maximum speed of 15 ms^{-1} occurred in the coast of Jakarta in the afternoon during sea-breeze formation. Furthermore, when the sea-breeze is penetrating to the southern part of Jakarta, surface convergence zone formed over Jakarta tends to raise the sea-breeze rapidly into the air (Figure 9). When the air begins to diverge above surface low-pressure, the wind eventually flows outward to both south and north direction and it then suddenly converges with the southerly wind in the upper-level and leads to the subsidence of the wind behind the convergence zone. This southerly wind is the sea-breeze driven upward as a result of low pressure in the mountainous area and flow back to the sea. This sea-breeze front is located around 40 km inland from the coast of Jakarta. In addition to low and high pressure in the surface and upper-levels, this front is also strongly developed while marine air from the Java Sea driven by sea-breeze converges with surface dry air over central Jakarta. A study conducted by Sofyan *et al.* (2005) also indicated the existence of this front over Jakarta which leads to the formation of shallow stable layer over Jakarta city.

As a polluted city, this convergence structure along with light wind flow inward will responsible for the potential pollutant trapped and mixed with other chemical compounds. During nighttime, as a result of UHI effect, another local wind circulation is developed so-called the country-breeze as shown in figure 10. This country-breeze flow from the rural areas into the city and developed well in relatively calm night at 2.00 LST, and another convergence structure developed with weakly wind circulation at 900 hPa over the city. This country breeze may also carry pollutant and dust from the rural areas aloft. The particulate matter mostly comes from the west where factories and international airport is located. Consequently, it suspend and dense over the city with vast quantities and further enhance the severe air pollution period in Jakarta.

Conclusions

MM5 model was performed to study the effect of UHI in Jakarta. MM5 modified land cover model to the simulated-temperature over Jakarta city and its surrounding areas showed that higher temperature was observed in the city during daytime, meanwhile in the nighttime, the effect of UHI was apparently well-observed since warmer temperature occurred in the city. Due to thermal city expansion, this effect increases the west rural area temperature. Warm temperature in the city is also influenced by the sea temperature where heat is released into the air. Local wind-driven then strengthens the warm temperature in the city at night. In order to achieve a better understanding of UHI effect, long-term simulation is required. Thus, the daily diurnal cycles of air temperature and their differences can be well-observed. Simulated-heat index in central Jakarta might result in a light heat-stress danger effect; that is, fatigue due to intensive physical activities. The sea-breeze was well-developed in the afternoon with MM5 modified land cover model. The sea-breeze front was also developed over surface convergence zone as a result of vertical pressure gradient. In addition, marine air from Java Sea strongly intensifies the convergence structure over central Jakarta.

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