The Cooling Effect of Green Strategies Proposed in the Hanoi Master Plan for Mitigation of Urban Heat Island

Andhang Rakhmat Trihamdani, M.Eng.  
[Grad. School for IDEC, Hiroshima Univ., Japan]  
andhang.rt@gmail.com

Han Soo Lee, Dr.  
[Grad. School of Science and Engineering, Saitama Univ., Japan]

Tran Thi Thu Phuong, M.Eng.  
[Vietnam Institute Urban and Rural Planning, Vietnam]

Tetsu Kubota, Dr.  
[Grad. School for IDEC, Hiroshima Univ., Japan]

Takahiro Tanaka, Dr.  
[Grad. School of Engineering, Hiroshima Univ., Japan]

Kaoru Matsuo, M.Eng.  
[Grad. School of Engineering, Hiroshima Univ., Japan]

**ABSTRACT**

This study aims to assess the impacts of land use changes brought by the Hanoi Master Plan on its urban climate using the Weather Research and Forecasting (WRF), focusing on the cooling effect of the green strategies that were proposed in the master plan. The results show that even after implementing the master plan, the peak air temperature in the urban areas still remains at the same level of 41°C. However, the expansion of built-up areas largely increases the UHI intensity and raises the nocturnal air temperatures in the built-up areas. The centralized green spaces proposed in the master plan is seen to be insufficient to mitigate UHIs compared to the equally distributed green spaces. The urban air temperature in Hanoi is increased when the westerly or south-westerly Foehn winds flow over the city during the daytime. In contrast, relatively strong and cool southerly winds prevail during the night-time and contribute to reduction in the nocturnal air temperature in the city.

**INTRODUCTION**

Emerging economies in Southeast Asia are likely to see serious energy shortages, especially in terms of electricity, due to the recent rapid economic growth. Most of the cities in this region have a hot and humid climate during the summer months, and the growing energy consumption caused by air-conditioning in buildings is, therefore, a major concern. Meanwhile, these cities are suspected of already experiencing urban heat islands (UHIs) as a result of the rapid urbanization. The further rise of urban temperature would lead to a significant increase in energy demand for cooling. Currently, these Southeast Asian cities tend to propose large-scale master plans and increase their urban population. This would result in a dramatic change in land use and therefore the urban climate.

In Hanoi, a long-term urban development plan, namely the Hanoi Master Plan 2030, was implemented in 2011 with the aim of developing the city into a more sustainable capital (VIUP, 2011). One of the key concepts of the master plan is to maintain abundant green coverage in the city through a systematic green network, including green buffers and green belts, for example. Although the master plan had considered various environmental issues such as air pollution, water quality and eco-system, this assessment did not take into account the impact of this development on UHIs in the city.
Therefore, the objective of this study is to investigate the UHI effects in Hanoi under the present land use conditions as well as under those conditions proposed by the master plan, focusing especially on the cooling effects of the green strategies. Numerical simulations, specifically meso-scale urban climate modelling using Weather Research and Forecasting (WRF) are performed for this purpose.

HANOI MASTER PLAN 2030

As the capital city of Vietnam, Hanoi is the second largest city of the country, which make up an area of about 3,300 km$^2$. The city center is located in the delta area along the Red River, which is about 90km inland from the coastal line. Hanoi experiences a typical tropical monsoon climate, comprising a hot-humid season (April to October) and a cool and relatively dry season (November to March). The southeast monsoon wind prevails during the hot season. The maximum monthly average air temperature is observed in June, which is about 30°C, while the minimum average value of about 16.5°C in January.

![Figure 1](image)

**Figure 1** Land use and land cover for (a) the current status and (b) the Hanoi Master Plan 2030. Source: VIUP, 2011

The Vietnam government officially implemented the Hanoi Master Plan 2030 in July 2011. In the master plan, the population of Hanoi is projected to reach 9.2 million by 2030. The main target of the master plan is to develop Hanoi as a green-cultured and civilized-modern city. In order to achieve that target, the master plan proposes a series of spatial development strategies for the capital city. One of them is, as described before, the green network consisting of two major green strategies which are the green belts and the green buffers. As a result, the green coverage in the master plan would account for about 52% of the total land of the city. Figure 1 shows the land use changes before and after the implementation of the master plan. To meet the demand of expanding urban development, 28% of the city’s natural land will be allocated for urban construction land by 2030. In total, the constructed land will rise sharply by almost three times, from 46,340 ha (14%) to more than 129,500 ha (39%).

DATA AND METHODOLOGY

Weather Research and Forecasting

Meteorological modelling is performed to obtain basic weather elements such as air temperature, humidity, and surface wind, using the Advanced Research Weather Research and Forecasting (WRF-ARW) model (version 3.5) (Skamarock et al., 2008). WRF is a three dimensional non-hydrostatic meso-scale meteorological model developed at the National Center for Atmospheric Research (NCAR) based on the non-hydrostatic compressible form of the governing equations in spherical and sigma coordinates with physical processes, such as cumulus scheme, microphysics, planetary boundary layer (PBL) processes and atmospheric radiation processes, incorporated into a number of physics parameterizations. This model has been widely used in atmospheric research and operational forecasting needs.
Figure 2  (a) Computational domains for the WRF simulation. (b) Domain 4 covers all of Hanoi City (100x100 grid points), with 1 km resolution. The green strategy areas are indicated by colors. Green represents the green belts and red is for the green buffers.

The WRF simulations in this study adopt an interactive grid nesting with four domains that have horizontal resolutions of 27, 9, 3 and 1 km for domains 1, 2, 3 and 4, respectively (Figure 2a). The domain 4 covers all of the Hanoi City (Figure 2b). The 30 sigma levels are set up vertically. The initial and lateral boundary conditions are imposed every 6 hours using the NCEP FNL Operational Global Analysis data with 1°x1° latitude-longitude resolution (http://rda.ucar.edu/datasets/ds083.2/).

Simulation scenarios

As shown in Figure 2b, the green belts are large green spaces located inside the urban development area with the aim of improving the micro-climate conditions, while the green buffers are the boundary space between the existing urban areas and expanded urban clusters. To study the effect of these strategies on the urban climate in the future, a comparison is performed between the current condition (hereafter referred as U_CUR) and the master plan scenario (hereafter referred as U_HMP). Both of the green strategies are implemented in the U_HMP. In order to evaluate the effectiveness of the green strategies, two scenarios are designed which are U_NOGREEN and U_GREEN. In U_NOGREEN, both of the green strategies are not taken into account and converted into the built-up area (Figure 3c). Meanwhile in U_GREEN, the same amount of strategic green areas in the master plan are redistributed to new locations, resulting in smaller green spaces but equally distributed in all of the city (Figure 3d).

Figure 3  LULC of domain 4 for (a) U_CUR, (b) U_HMP, (c) U_NOGREEN, and (d) U_GREEN.

Model validation

The simulation was conducted for one month from 00:00 UTC 1 to 00:00 UTC 30 June in 2010, which was the hottest period over the period of 2000-2012. Subsequently, simulation results on 17 June of a typical hot sunny day is mainly analyzed in the following sections. Figure 4 presents the comparison of air temperature and wind speed between the simulated and the 3-hourly observation data at Lang station (21.02°N 105.8°E) located in the Hanoi city center (see Figure 1a). Both of the simulated air temperature (at 2 m above ground surface) and wind speed (at 10 m above ground surface) show good
agreement with the observed values with a coefficient of determinant of 0.92 and 0.13, respectively. The simulation conditions are shown in Table 1.

![Comparison between the observed and simulated value for (a) air temperature and (b) wind speed at Lang station located in Hanoi city center.](image)

**Figure 4** Comparison between the observed and simulated value for (a) air temperature and (b) wind speed at Lang station located in Hanoi city center.

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**RESULTS AND DISCUSSION**

**Urban climate in current status and master plan condition**

Figures 5 and 6 present the spatial patterns of the simulated air temperature at 2 m above the ground surface and the winds at 10 m above the surface for U_CUR, U_HMP, U_NOGREEN and U_GREEN at 1:00 and 16:00 LST on 17 June, respectively. This section compares U_CUR and U_HMP. At night, the highest air temperature is observed not in the city center but in the lee of western mountainous region in both scenarios (Figure 5). This result is partly due to the effect of Foehn wind from Laos (Nguyen & Reiter, 2014). As shown in Figures 5 and 6, westerly or south-westerly winds prevail most of the day in the western mountainous region. While these westerly winds pass over the mountain range situated near the border of the Hanoi region, the air gets drier and the temperature increases rapidly. These westerly winds flow over most parts of the simulated area during the daytime (9:00-17:00) and bring hot and dry air to the city. In contrast, relatively cool south-easterly or southerly winds prevail over plain areas in the east of 105.65°E during the night-time (18:00-8:00) (Figure 5).

In U_CUR, the minimum nocturnal air temperatures in urban and suburban areas are recorded as approximately 31-32°C, while the air temperature is approximately 32-33°C in the lee of mountainous areas. The daily peak air temperatures were obtained in most parts of the city around 16:00 in both conditions (Figures 6a and 6b). Although the peak air temperatures remain almost the same level even after implementing the master plan, the high air temperature areas of 40-41°C expand widely over the planned built-up areas in U_HMP. At 1:00, the air temperature difference between U_CUR and U_HMP increases by up to 2-3°C over the expanded built-up areas under the master plan condition. During the daytime, the increase in air temperature over the expanded built-up areas is not significant, which is up to 1°C, compared to that in the night-time.
Master plan condition and that without green network

In U_NOGREEN, the planned green spaces are turned into the built-up areas. As expected, the high air temperature areas of 33-34°C are enlarged over the expanded built-up areas at 1:00 (Figure 5c), while the high air temperature areas of 40-41°C are found over the same expanded built-up areas at 16:00 (Figure 6c). The increase in air temperature in the built-up areas becomes noticeable during the nighttime (1:00), with the maximum increase of 1°C from U_HMP to U_NOGREEN. The incremental zones of the air temperature from U_HMP to U_NOGREEN correspond to the expanded built-up areas and those transformed from the planned green spaces.

The diurnal average air temperatures of seven days (13-20 June) in Lang and Tu Liem for three scenarios are shown in Figure 7. These two locations represent the existing city center (Lang) and the green areas located in the green belt (Tu Liem), respectively (see Figure 1a). As shown, the average air temperatures for U_CUR and U_HMP at Tu Liem are lower than the corresponding air temperatures at Lang by up to 1°C during the nighttime and by up to 0.5°C during the daytime, respectively. This is mainly due to the difference of land cover between the two places. Tu Liem still maintains the natural land cover (i.e. mixed shrubland or grassland) even after the implementation of the master plan. However, if all the green areas are converted to built-up areas, the air temperatures at Tu Liem are increased significantly by up to 1.5°C at night, reaching the similar values to those at Lang. Meanwhile, the removal of green strategies results in a slight increase in the average air temperatures in the existing city center (i.e. Lang). As shown in Figure 7a, the nocturnal average air temperatures in U_NOGREEN are approximately 0.3°C higher than those in U_HMP.

As shown in Figure 7, in both Lang and Tu Liem, the average air temperatures in U_CUR increase slightly faster than those in the other scenarios during the morning hours from 8:00 to 10:00. This occurs, although not prolonged, probably due to the difference of heat capacity of the whole urban fabric between U_CUR and the other scenarios. Thermal capacity of the whole urban surface is largely increased by the expansion of the city, which in turn, slows the increase in air temperature during the morning in the cases of U_HMP and U_NOGREEN than that in U_CUR. On the other hand, the green areas induce a relatively faster heat release as illustrated in Figure 7b. As shown, except for the above mentioned morning hours, the average air temperatures in U_CUR and U_HMP in Tu Liem are significantly lower than those without the green areas (U_NOGREEN). Nevertheless, the proposed green areas do not result in the large reduction in air temperature at Lang because the city center is located 4
km away from the green belt.

![Figure 7](image)

**Figure 7** Diurnal variation of average air temperature over seven days (13th-20th June) at (a) Lang and (b) Tu Liem.

### Impacts of the distribution of green spaces

Figure 8 shows the air temperature distribution over the built-up areas in U_HMP and U_GREEN at 1:00 and 16:00 on 17th June 2010, respectively. As shown in Figure 8a, the nocturnal air temperatures in the built-up areas range from 31-34.5°C, with the proportion of the area at specific temperature peaking at 33.5°C. In U_GREEN, the proportions of the area with the air temperature of 32.5-34°C are reduced, while the proportions of the area with the lower air temperatures of 31-32°C are increased. This air temperature shift indicates the reduction in UHI intensity after the green spaces are equally distributed within the city. In the daytime, the amount of areas with the air temperature of 39.5°C is reduced and shifted down to the ranges of 38.5-39°C, indicating the temperature reduction by 0.5-1°C (Figure 8b). The impact of the relocation of the green spaces on the reduction of UHI intensity is greater in the nighttime than that in daytime.

![Figure 8](image)

**Figure 8** Air temperature distribution over the built-up areas on 17th June at (a) 1:00 and (b) 16:00.

### Effects of prevailing winds

Figure 9 depicts wind roses at the city center (Lang) over the one month simulation period (June 2010) analyzed by the corresponding air temperatures (a, b) and the wind speeds (c, d) at 10 m above the ground surface during the daytime (09:00-17:00) (a, c) and the night-time (18:00-08:00) (b, d), respectively. It is noted that the three scenarios did not show any remarkable differences in terms of ground surface wind conditions (see Figures 5 and 6). Therefore, the data from U_CUR are analyzed in this section.

As seen in the previous section, the southerly and south-easterly winds with relatively high wind speeds of 4-7 m/s prevail during the night-time over the whole month (Figure 9bd). In contrast, the prevailing wind direction differs during the daytime as shown in Figure 9ac. The westerly or south-westerly winds prevail over approximately 38% of the month (Figure 9ac). Nevertheless, the north-easterly and south-easterly winds also prevail during the same period. It is interesting to note that when the westerly or south-westerly winds blow over the city center, the air temperatures are relatively higher (38-41°C) than the air temperatures under the conditions of north-easterly or south-easterly winds (28-40°C), though the corresponding wind speeds do not differ significantly between the different wind directions (Figure 9ac). This result supports the assumption that urban air temperature in Hanoi is increased when the westerly or south-westerly Foehn winds flow over the city during the daytime.
Figure 9  Wind roses at Lang station in June 2010, analyzed by (a) air temperature (daytime), (b) air temperature (night-time), (c) wind speed (daytime), and (d) wind speed (night-time).

Figure 10  Variations in the simulated air temperature and wind speed from U_HMP and U_NOGREEN along the west-east cross-section of the meridional line at 21.04°N.

Figure 11  Variations in the simulated air temperature and wind speed from U_HMP and U_NOGREEN along the south-north cross-section of the meridional line at 105.81°E.
Figures 10 and 11 show the spatial variations in the air temperature and wind speed along the cross sections (see Figure 2b) of domain 4 from U_HMP and U_NOGREEN on 17 June. The horizontal indicator for the LULC category in each panel is based on the master plan. Therefore, from Figures 10 and 11, the effects of the green spaces and surface winds on the air temperature can be discussed. This cross-section traverses two mountains at heights of approximately 260 m and 280 m in the western region at 105.22°E and 105.40°E, respectively.

The discrepancies between the air temperatures in the strategic green areas under U_HMP and the built-up transformed areas in U_NOGREEN are large, up to 2-3°C, when the relatively strong and cool southerly winds prevail at 1:00 (Figure 10a). In this circumstance, the reduction in the air temperature due to the effect of the green strategy can be observed in some parts of surrounding built-up areas, up to 1°C. These discrepancies are reduced in the daytime as the wind direction changes from the south to the west (Figure 10b). The surface wind conditions largely affect the air temperature distribution. As shown in Figure 10a, the leeward sides of both mountains receive relatively higher westerly winds and the air temperature increase while flowing down the slopes of the mountain at 105.4°E (i.e. the Foehn effect).

The southerly winds flow from the coastal area and pass through the irrigated croplands in the south at 20.85°N and bring relatively lower air temperature before entering the urban areas (Figure 11a). From the above point, the air temperature in U_NOGREEN gradually increases towards the north and then rapidly decreases. Then, the air temperature simulated in U_NOGREEN depicts a direct and linear response to the corresponding winds (Figure 11a). The cooling effect of the surface wind are clearly seen when the air temperature in built-up areas over the eastern half from 105.65°E drops by nearly 1°C particularly when the southerly winds prevail at night (see Figure 5ab and 10a).

CONCLUSIONS

Based on the results of the numerical experiments, the main findings are summarized as follows:

1. In general, the daytime peak air temperature rises up to 40-41°C over the built-up areas in the city center in the current condition.

2. If the LULC is changed according to the master plan, the daytime peak air temperature is predicted to remain at almost the same level as the current condition. However, the new hotspots would expand widely over the planned built-up areas.

3. The strategic green spaces would not sufficiently mitigate UHIs in the city because they are located far away from the city center. On the other hand, the equally distributed green areas show a better performance in the reduction of UHI intensity, especially at night.

4. The south-westerly or westerly winds are dominant in the daytime and bring hot and dry air to the city, likely due to the Foehn wind. The air temperature in Hanoi City is increased when these Foehn winds flow over the city during the daytime. The occurrence of this phenomenon was found to be approximately 38% in June 2010. In contrast, relatively strong and cool southerly winds prevail during the night-time and contribute to reduce the nocturnal air temperature in the city. Due to the discrepancy in term of wind condition, heat islands appearing in the western built-up region of Hanoi are found to be more intense than in the city center at night.

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REFERENCES

