Andhang Rakhmat Trihamdani

Urban heat islands in the future Hanoi City: Impacts on indoor thermal comfort and cooling load in residential buildings

Andhang Rakhmat Trihamdani[1], Nguyen Huy Tung[1], Tetsu Kubota[1], Han Soo Lee[2], Tran Thi Thu Phuong[3]

[1] *Graduate School for International Development and Cooperation, Hiroshima University, Japan*

[2] *Graduate School of Science and Engineering, Saitama University, Japan*

[3] *Vietnam Institute of Urban and Rural Planning, Ministry of Construction, Vietnam*

Abstract

This study aims to evaluate the impacts of future warmed urban climate on the indoor thermal comfort and cooling load in residential building in Hanoi. Firstly, the urban climate simulations using Weather Research and Forecasting (WRF) were conducted under the current climatic condition, Hanoi master plan scenario and the proposed UHI mitigation scenario. Secondly, the indoor thermal comfort and cooling load were evaluated by using building simulation program, TRNSYS. The results show that the implementation of Hanoi Master Plan 2030 is predicted to increase the number of hotspots and raise the air temperatures in the built-up areas by up to 2-3°C. The large and centralized green spaces currently proposed in the master plan were found to be less effective to minimize the impact of UHI, compared with the smaller but equally distributed green areas. Furthermore, the results of thermal comfort evaluation show that if a row house in rural area is situated in the urban area in the future due to the expansion of the city, then the indoor operative temperature is predicted to increase by up to 1.6°C. Consequently, after the implementation of the master plan, the cooling load would increase significantly by up to 179% in the future.

1. Introduction

In Hanoi, Vietnam, a long-term urban development plan, namely the Hanoi Master Plan (HMP) 2030, was implemented in 2011 with the aim to develop the city to be a sustainable capital (VIAP, 2009). A series of green network in the city was proposed in HMP. However, the effects of the mentioned green network for mitigating urban heat island (UHI) have not been evaluated, though maximizing the thermal benefits of the urban green spaces has been reported to offer a solution for ameliorating the urban climate.

About 69% of the building stocks in Vietnam is dominated by the 3-5 storey row houses (Parkes, 2013). The climatic condition due to UHI is predicted to make the achievement of thermal comfort by natural ventilation more difficult in those buildings. As consequences, the occupants will be forced to use the air conditioning (AC) in order to achieve their thermal comfort. Thus, the energy consumption for cooling is predicted to increase.

The objective of this study is to investigate the UHI effects under the present land use condition, the master plan, as well as under the UHI mitigation scenario on the thermal comfort and cooling load of the urban row house in Hanoi. Numerical simulations, specifically meso-scale urban climate modelling using Weather Research and Forecasting (WRF) and building simulation using TRNSYS are performed for this purpose.

2. Impacts of land use change on the future climate of Hanoi City

2.1 Methods

Meteorological modelling is performed using the Weather Research and Forecasting (WRF) (Skamarock et al. 2008). The present study used WRF version 3.5, known as the Advanced Research WRF (ARW), which was developed by the National Center for Atmospheric Research (NCAR). The WRF simulations 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 1a). The domain 4 covers the whole administrative boundary of the Hanoi City (Figure 1b). The vertical layer we set is up to 30 sigma levels. The initial and lateral boundary conditions are imposed using 6-hourly NCEP FNL (Final) Operational Global Analysis data.

2.2 Simulation scenarios

In the HMP 2030, the green belts form large and centralized green areas in the city (Figure 1b). To study the effect of those proposed green network on the urban climate, a comparison is performed between the current condition (hereafter referred as Case 1) and the master plan scenario (hereafter referred as Case 2). Further, the same amount of the green belts in the master plan is relocated into new locations, resulting in smaller green spaces but equally distributed in the city, namely Case 3 (Figure 2).

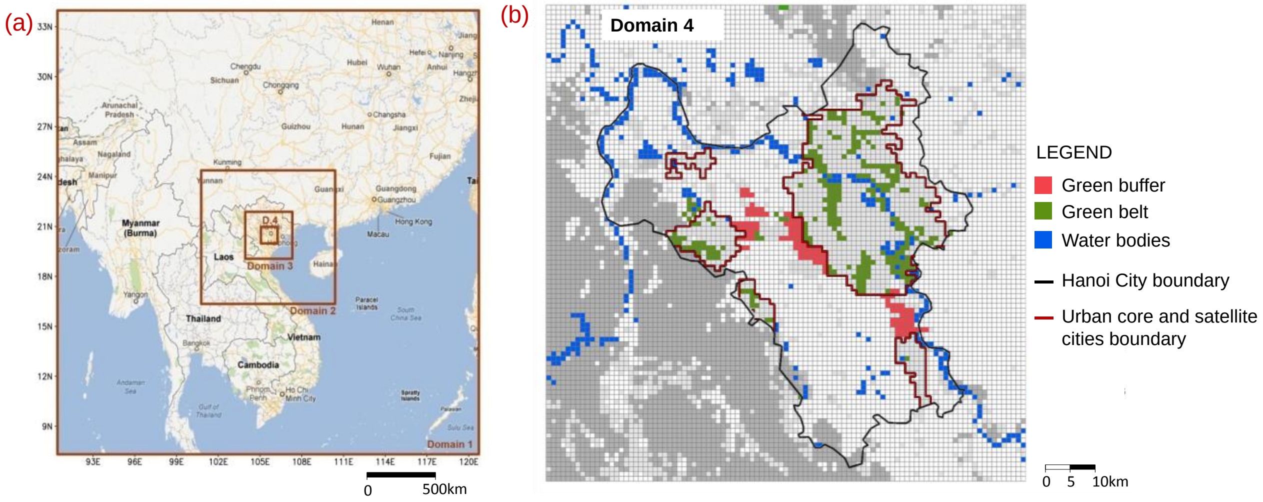

Figure 1 (a) Computational domains for the WRF simulation. (b) Domain 4 covers all of Hanoi City (100x100 grid points), with 1 km resolution. The green strategy areas are indicated by colors.

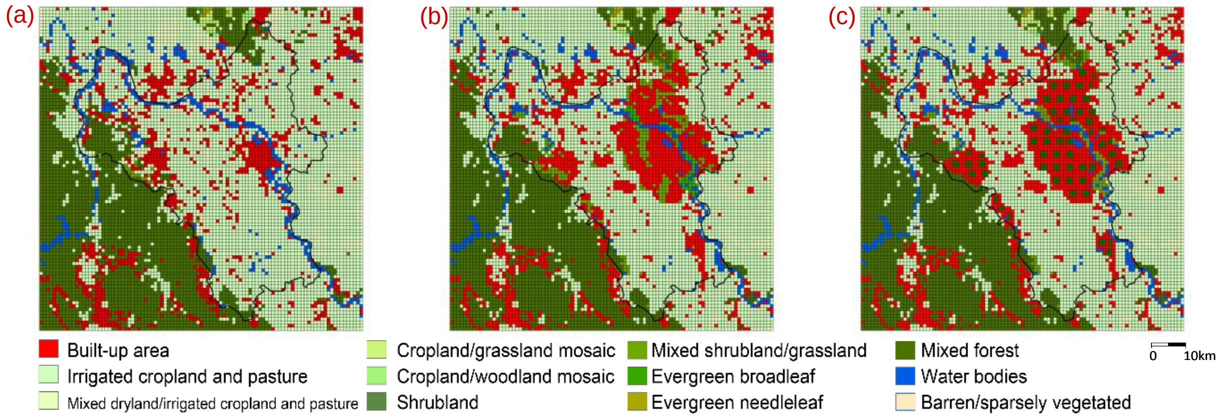

Figure 2. LULC of domain 4 for (a) Case 1, (b) Case 2 , and (c) Case 3.

2.3 Land use land cover (LULC) data

The USGS 24-categories LULC data were used for domains 1 and 2. For domain 3, Global Land Cover by National Mapping Organization (GLCNMO) version 1 was used. The LULC for domain 4 for Cases 1 and 2 applied the combination between the ALOS satellite image and the national digital map provided by Vietnam Institute of Urban and Rural Planning (VIUP). The digital map only covers the land use within the Hanoi administrative area. In order to fill the remaining area, the land cover detected from ALOS AVNIR-2 satellite image was used. The LULC in Case 3 was configured by modifying the LULC of Case 2. Firstly, the green belts in Case 2 were removed and turned into the built-up areas. Then, the removed green spaces were redistributed back in the Hanoi City (Figure 2c).

2.4 Model validation

The WRF simulation was conducted for one month from 00:00 UTC 1 to 00:00 UTC 30 June in 2010, which was the hottest month over the year 2000 to 2012. Figure 3 presents the comparison of air temperature, wind speed and wind direction between the simulated and 3-hourly observation data at Lang station (21.02°N 105.8°E) located in the Hanoi city center. Both of the simulated air temperature (at 2 m) and wind speed (at 10 m) show good agreement with the observed values with a coefficient of determinant of 0.92 and 0.13, respectively. In addition, the wind rose at 10 meter also shows good agreement with the 3-hourly observational value (not shown in this manuscript). The detailed WRF parameterization is summarized in Table 1.

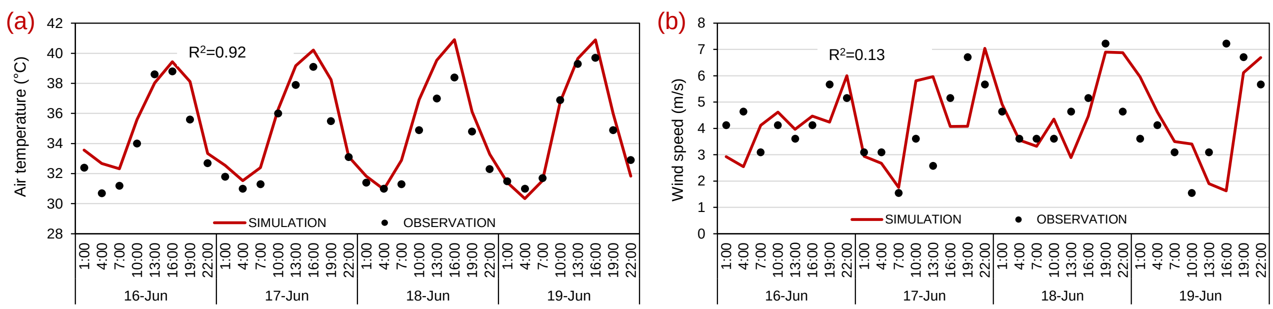

Figure 3. Comparison between the observed and simulated value for (a) air temperature and (b) wind speed.

Table 1. WRF Simulation Conditions

Items	Conditions
Simulation period	00:00 UTC 1 to 00:00 UTC 30 June in 2010
Meteorological data	NCEP FNL
Microphysics	WSM 3-class
Long-wave radiation	RRTM long-wave scheme
Short-wave radiation	Dudhia short-wave scheme
PBL scheme	YSU Scheme
Cumulus scheme	Kain-Fritsch scheme
Surface scheme	NOAH-LSM
Surface layer	Monin-Obukhov scheme

2.5 Climatic zoning

The climatic conditions varied among the days. For example, the air temperature was very high due to the westerly Foehn wind during a particular period of this month (Nguyen and Reiter, 2014). Therefore, we classified the days in June 2010 into four periods, based on the similarity of air temperature and wind conditions, namely cool, warm, hot, and hottest period, respectively. The analysis in this study mainly focuses on the cool and hottest period.

Furthermore, for the thermal comfort and cooling load analysis, the whole area of domain 4 were classified into several climate zones with similarities in terms of the air temperature and wind conditions, using the principal component analysis (PCA) and cluster analysis. The climatic zoning was applied for all cases. The hierarchical cluster analysis was adopted by using the Ward's method and Squared Euclidean distance measures. The results of the climatic zoning will be mainly used for the indoor thermal comfort evaluation and cooling load simulation.

2.6 Results and discussion

Figures 4 and 5 show the spatial distribution of air temperature at 2m and the winds at 10m above the ground for Cases 1,2, and 3 at 1:00 and 16:00, respectively, averaged from the results in the cool period. In this period, the peak average air temperature reached 34°C in all cases. Although the peak air temperature remain almost at the same level even after the implementation of the master plan, the hotspots expand widely over the planned built-up areas in Cases 2 and 3 (Figure 4bc). The air temperature in the new hotspot areas increased by up to 2-3°C from the current condition. Meanwhile, the air temperature in the green areas is 1°C lower than that in the built-up areas in all cases. In contrast, the peak nocturnal air temperature increased by up to 1°C after the implementation of the master plan. The new hotspots with air temperature of 29°C existed in the northwest part of the urban core in Case 2 (see Figure 5b). Interestingly, the hotspots were reduced under the new configuration of green spaces in Case 3 (Figure 5c).

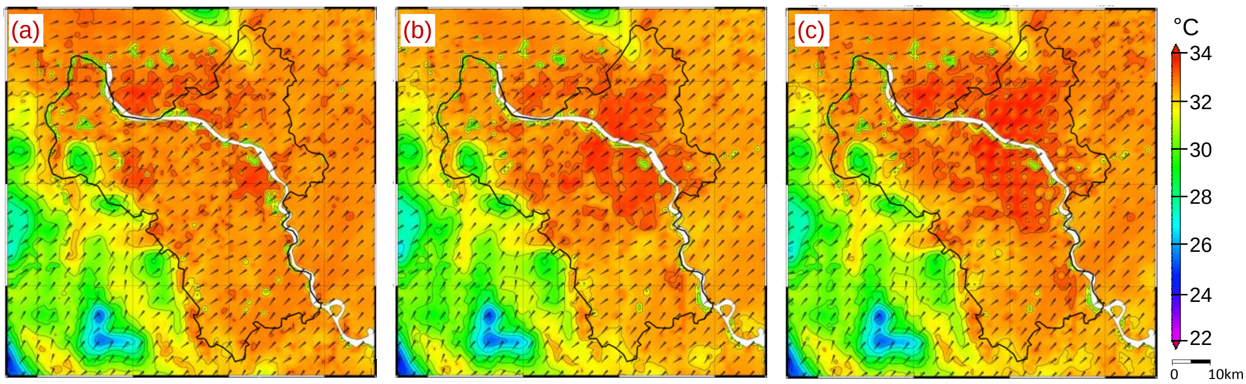

Figure 4. Spatial distribution of air temperature (2m) and wind conditions (10m) for (a) Case 1, (b) Case 2, and (c) Case 3 at 16:00 averaged from the results in cool period.

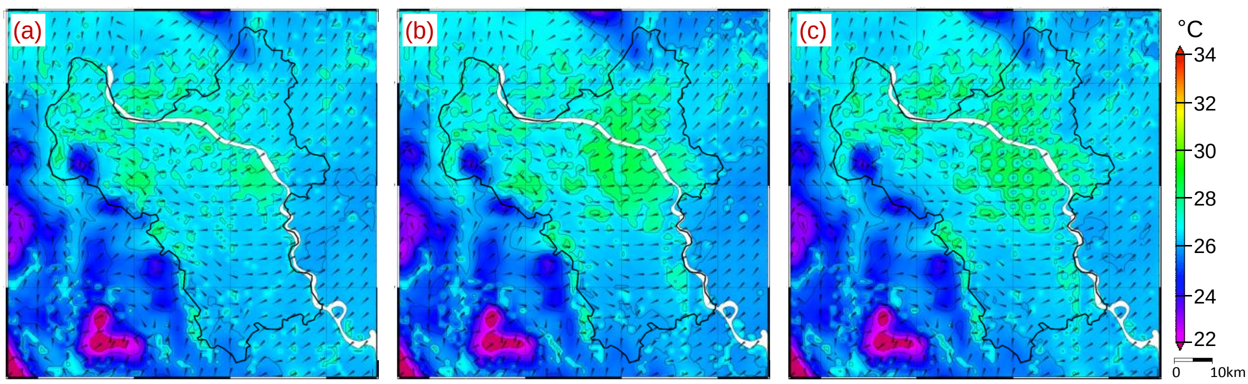

Figure 5. Spatial distribution of air temperature (2m) and wind conditions (10m) for (a) Case 1, (b) Case 2, and (c) Case 3 at 1:00 averaged from the results in cool period.

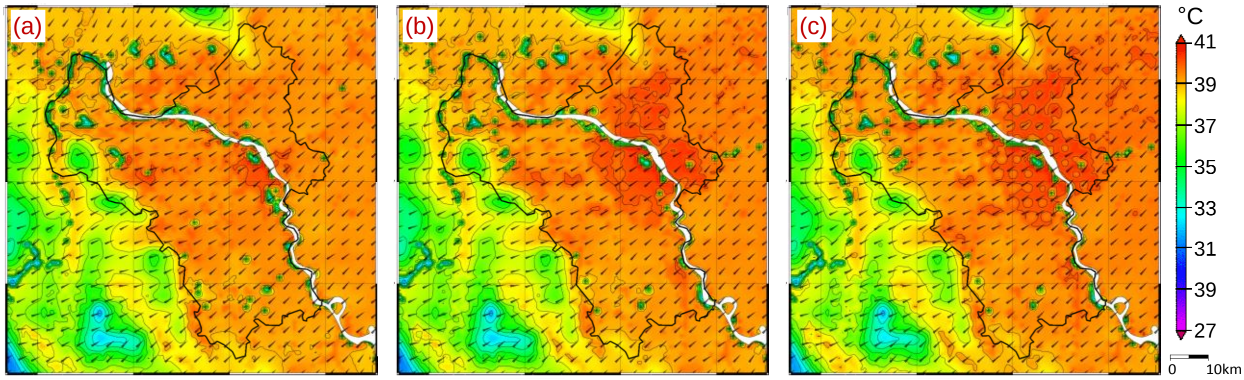

Figure 6. Spatial distribution of air temperature (2m) and wind conditions (10m) for (a) Case 1, (b) Case 2, and (c) Case 3 at 16:00 averaged from the results in hottest period.

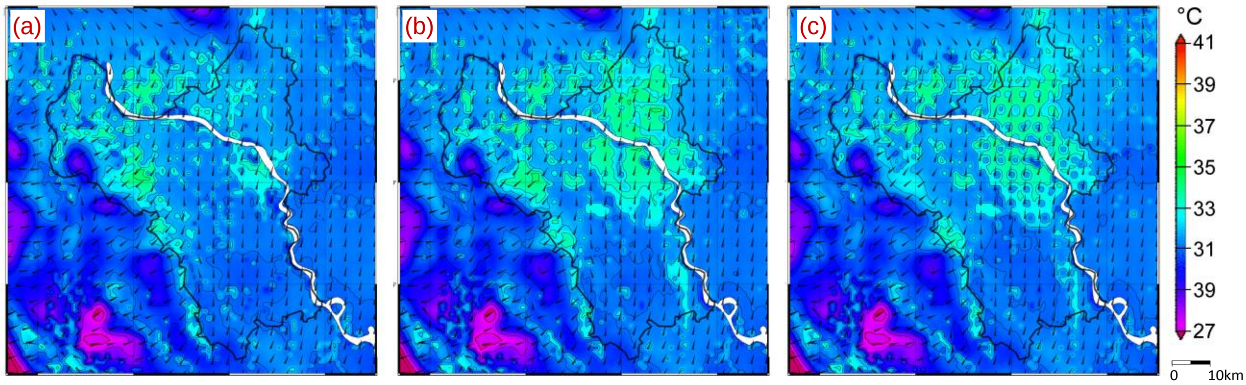

Figure 7. Spatial distribution of air temperature (2m) and wind conditions (10m) for (a) Case 1, (b) Case 2, and (c) Case 3 at 1:00 averaged from the results in hottest period.

Figures 6 and 7 present the results in the hottest period. In this period, the Hanoi City experienced the Foehn wind that blows from the mountainous region located in the western part of the city. These westerly winds increased the air temperature significantly, up to 40-41°C. These winds prevail in all over the city during the daytime. In the night-time, the southerly winds prevail in the eastern part of the city while the westerly winds are still prevailing in the western part of the city. The discrepancy of wind condition in the city caused a condition in which the air temperature in the western part of the city was higher than the eastern part (see Figure 7a).

After the implementation of the master plan, the peak air temperature still remains at the same level with the current condition even in the hottest period, which is up to 41°C. In the night-time, the peak air temperature increases by up to 1°C (Figure 7b). Though the increment of nocturnal air temperature is similar with the cool period, the occurrence of hotspots with air temperature of 41°C is larger than that in the cool period.

Figure 8 shows the diurnal average of air temperature in all built-up areas in both periods. The small and equally distributed green space configuration employed in Case 3 results in a lower average air temperature than the proposed green networks in HMP. The reduction in average air temperature reached 0.5°C in the night-time and 0.3°C in the daytime under the hottest period.

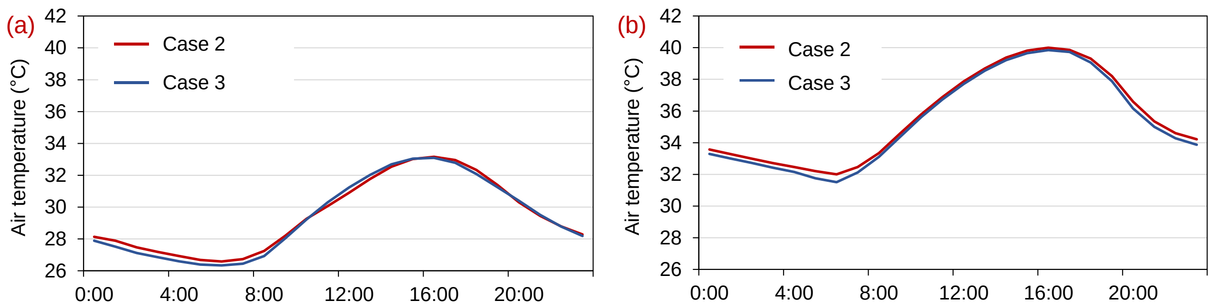

Figure 8. Diurnal average of air temperature in built-up areas for (a) cool period and (b) hottest period

3. Thermal comfort evaluation for typical urban row house

3.1 Methods

A building model of a typical urban row house was developed based on the analysis of about 300 building drawings. The building simulation was conducted by using the TRNSYS (Klein, S.A. et al). All the elements of the building and its surrounding conditions were considered in the simulation. The model was oriented towards north. The thermal properties of building material were determined based on those suggested by the Vietnam government (Ministry of Construction, 2013). The schedules of room occupancy and usage of household appliances were decided based on the results of the interviews and previous study (Le Phan and Yoshino, 2010). The household size was assumed to be four persons. Moreover, night ventilation was adopted in all rooms.

The simulation model was validated with the measurement data obtained from the field measurement. Overall, the results show good agreements with the measurement data with coefficient of determination (R^2) of 0.82-0.97 for temperatures and 0.81-0.87 for absolute humidity, respectively.

We adopted the weather data resulted from climatic zoning as the input for TRNSYS (not included in this manuscript). Firstly, we selected the zones that represent the majority of urban and rural areas in Cases 1,2, and 3, respectively. Then, the daily average weather data from each of the respective zones were used for the simulation. Therefore, the results will represent the thermal comfort on the daily basis during the summer month under the typical climatic conditions of urban and rural areas.

The indoor thermal comfort was evaluated by using the adaptive comfort equation (ACE), which was developed for the use in hot-humid climates (Toe and Kubota, 2013). The 80% comfort limit is given as a function of daily mean outdoor air temperature. The operative temperatures were compared with the 80% comfort limit to calculate the deviations from the limit as well as their exceeding periods. In other words, when the indoor operative temperature is above the required upper limit, it will be considered as the discomfort period, and then the number of hours of those periods are calculated to be the percentage of exceeding period.

3.2 Results and discussion

Figures 9 and 10 show the indoor operative temperatures at different floor levels obtained through simulations in the Cases 1, 2, and 3 respectively during the cool and hottest periods. The straight lines indicate the ACE 80% upper comfortable limit. Table 2 presents the summary of thermal comfort evaluation.

Overall, hot outdoor temperatures due to the Foehn phenomenon in the hottest period largely affect the indoor operative temperatures (Figure 10). Except for the ground floor, the exceeding periods reached 100% during this period (see Table 2). In contrast, during the cool period, the thermal comforts are fully achieved throughout the day at the ground floor in all cases, while the upper floors (1F-3F) can merely achieve the thermal comfort in some hours during the night and morning time (see Figure 9).

In general, the exceeding period of the row house in rural areas is shorter than in urban areas. Nevertheless, if a row house in the rural areas of Case 1 is situated in the urban area of Case 2 due to the expansion of the city, the indoor operative temperature is predicted to increase by 0.5-1.1°C in the cool period and 1-1.6°C in the hottest period. In that case, the exceeding period is predicted to increase by up to 46% during the cool period and 42% in the hottest period. Moreover, the exceeding periods on the ground floor in Case 3 are lower by 8% compared to Case 2 during the hottest period.

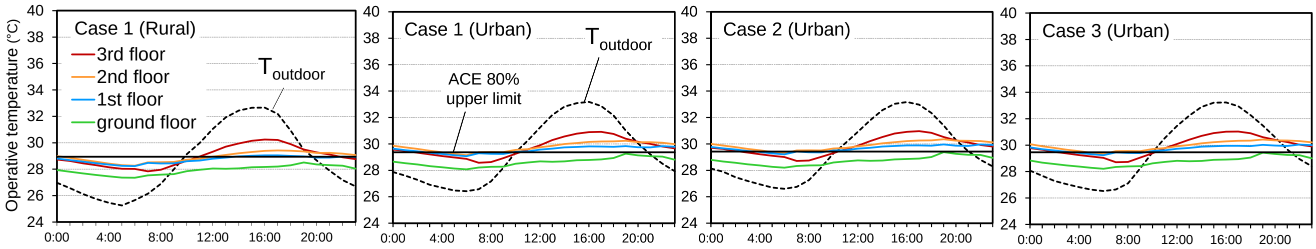

Figure 9. Thermal comfort evaluation in cool period

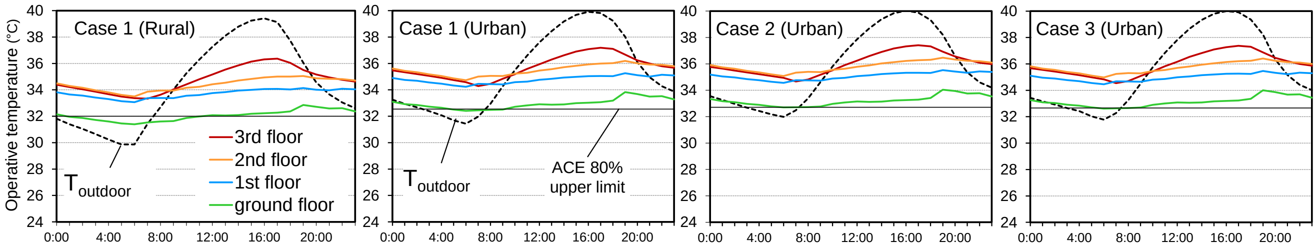

Figure 10. Thermal comfort evaluation in hottest period

Table 2. Summary of thermal comfort evaluation

Floor level	Cool period				Hottest period			
	Case 1		Case 2	Case 3	Case 1		Case 2	Case 3
	Rural	Urban	Urban	Urban	Rural	Urban	Urban	Urban
	Exceeding period (%)				Exceeding period (%)			
GF	0	0	0	0	54	79	96	88
1F	29	71	75	75	100	100	100	100
2F	54	88	92	92	100	100	100	100
3F	46	63	67	67	100	100	100	100

4. Cooling load in typical urban row house

4.1 Methods

Cooling load was calculated in master bedroom (1st floor) of the row house under the assumption that AC will be used if the night ventilation cannot achieve the thermal comfort during the duration of 22:00 to 3:00, using TRNSYS. The above duration was determined based on the survey conducted in Hanoi (Le Phan and Yoshino, 2010). The weather data for TRNSYS were derived from the data that were used in thermal comfort evaluation.

4.2 Results and discussion

Figure 11 shows the results of cooling load simulation in the cool period and the hottest period, respectively. In general, the cooling loads of the row house in rural areas are lower than those in the urban areas under the Case 1 for both periods. Compared to the cool period, the cooling loads are much larger in the hottest period for all cases, mainly due to the Foehn phenomenon. The increments of the cooling loads from the cool period to the hottest period ranged from 97% to 415%.

In the cool period, if the row house in rural areas in Case 1 is situated in urban areas of Case 2 due to the expansion of the city, the cooling load is expected to increase from 11.9 MJ/day to 33.3 MJ/day (about 179%) (see Figure 11a). In the case of the row house situated in the urban areas in Case 1, the cooling load increases by up to 4.1 MJ/day due to the implementation of the master plan. Meanwhile, the cooling load in Case 3 is slightly higher than Case 2, with the increment of 0.45 MJ/day.

During the hottest period, if the row house in rural areas is situated in the urban areas in the future, the cooling load is predicted to increase from 61.6 MJ/day to 66.9 MJ/day (about 8.6%). The increment is smaller than in the cool period, mainly due to the duration of AC usage in the cool period was shorter than in the hottest period. Furthermore, the cooling load of Case 3 has slightly lower value than Case 2, which is 0.2 MJ/day (Figure 11b).

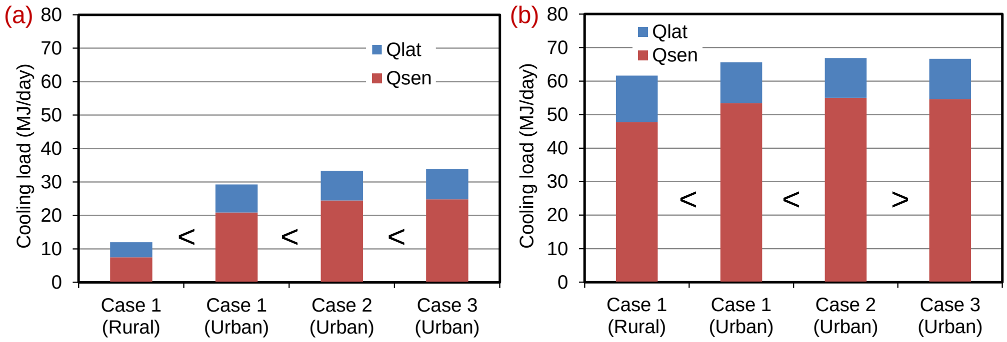

Figure 11. Sensible and latent cooling load for Case 1, Case 2, and Case 3 during (a) cool period and (b) hottest period. Q_{lat} is the latent cooling load while Q_{sen} is the sensible cooling load.

5. Conclusion

The main findings are summarized as follows:

1. The peak air temperature in summer is already very high (40-41°C) in Hanoi particularly when the westerly Foehn winds flow over the city.
2. The peak air temperature is predicted to remain at almost the same level as the current status even after the implementation of the HMP 2030. However, the hot spots would expand widely over the planned built-up areas.
3. The proposed green network in HMP may be effective in reduction of nocturnal air temperature, but they are not sufficient at cooling all of the built-up areas during daytime peak hours.
4. The newly proposed mitigation measure (small and equally distributed green areas) is slightly more effective at cooling nocturnal air temperatures than the present master plan.
5. If a row house in the rural area is situated in the urban area in the future, then the indoor operative temperatures are predicted to increase by 0.5-1.1°C in the cool period and 1-1.6°C in the hottest period.
6. After the implementation of the master plan, as the outdoor air temperature increases, the exceeding period from the comfort upper limit is increased thus raise the average cooling load in the row house by up to 33.3 MJ/day in the cool period and 66.9 MJ/day during the hottest period.

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