Impact Assessment of Urbanization on the Urban Thermal and Wind Environments

Masato Miyata*, Kaede Watanabe* and Satoru Iizuka**

Abstract:

In emerging countries such as post BRICs, land uses are expected to alter as urban areas expand because of rapid population growth and economic development (a process known as urbanization). Especially in extensive cities, land conversion may affect urban thermal and wind environments, and must be therefore considered in urban planning. An example is the Socialist Republic of Vietnam, with an annual population growth rate of 1.2%.

This study focused on Vinh City (Vietnam; approximate total area = 250 km2). The urban thermal and wind environments before and after urbanization were analyzed by the Weather Research and Forecasting (WRF) model, a fully compressible non-hydrostatic regional atmospheric model. Three scenarios were analyzed (Cases 1, 2 and 3) with a target year of 2030 and a population of 900,000. In addition, to assess the impact of urbanization on thermal and wind environments (temperature, humidity, and wind velocity), the urbanization patterns were surveyed under green coverage ratios of 30% and 60% in new residential districts.

According to the results, the maximum temperature increases (above Case 0) in the northern area were 0.71°C (at 12 pm (noon)), 1.05°C (at 2 am), and 0.26°C (at 9 pm) for Cases 1, 2, and 3, respectively. In the southern area, the respective maximum temperature increases were 1.65°C (at 12 pm), 1.50°C (at 12 pm), and 1.78°C (at 1 pm).

Increasing the green coverage ratio from 30% to 60% reduced the maximum temperature rise to 0.40°C. Thus, this study revealed that land use patterns and green coverage ratio significantly alter the urban environment variables. This result is important for master plan development.

Keywords:

Land Use, Urban Planning, Thermal & Wind Environments, Green Space

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* Nikken Sekkei Civil Engineering Ltd, **Nagoya University
E-Mail: miyata.masato@nikken.jp

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Introduction

In emerging countries such as post BRICs, land conversion is the expected result of rapid population growth and economic development, which leads to the expansion of urban areas (a process known as urbanization). Especially in extensive cities, land conversion may significantly affect the urban thermal and wind environments, and must therefore be considered in urban planning. A typical example is the Socialist Republic of Vietnam, whose population is growing at 1.2% per annum.

Population increase is concentrated in urban areas, and rapid urbanization has been noted in Vinh City, north-central Vietnam. Population growth is accompanied by increasing investment in urban development. Therefore, planning frameworks must be improved to accommodate these growths.

The proposed city master plan will expand the coverage of Vinh City to approximately 250 km^2 (this master plan is currently being reviewed by Nikken Sekkei Civil Engineering Ltd; 2014).

Assuming that planning over such a huge area will cause extensive land use conversion, the effect on urban thermal and wind environments should be considered, and the lowest-impact urbanization plan should be implemented. However, city master plans usually ignore social and economic aspects, which are also important. Thus, focusing on urban thermal and wind environments does not necessarily deliver the best plan.

This study covered the expanded Vinh City area. The urban thermal and wind environments before and after the urbanization were analyzed by the Weather Research and Forecasting (WRF) model, a fully compressible non-hydrostatic regional atmospheric model. Given a target year of 2030 and a population of 900,000, environments were analyzed for three urbanization patterns. In addition, to assess the impact of urbanization on the urban thermal and wind environments (temperature, humidity, and wind velocity), each urbanization pattern was surveyed at green coverage ratios of 30% and 60% in new residential districts.

Characteristics of the Study Area

Vinh City is located in the southern part of Nghe An province. Its geographical coordinates are 18°40′ North and 105°40′ East. It is surrounded by Ha Tinh province on the south, Nghi Loc district on the northeast, and Hung Nguyen district on the west. It is also located 219 km south of Hanoi and 1,400 km north of Ho Chi Minh City. The city is connected to the north–south traffic by National Highway 1A. Highways 7 and 8 connect Vietnam to Laos and the Northeast Thailand provinces. The Cua Lo seaport in Cua Lo Town connects Vinh to domestic and international trade routes. At present, Vinh Airport operates only domestic flights, but aspires to become an international airport in the near future.

The total land area of Vinh City (currently 105 km^2) is divided into 25 administrative units, 16 wards and 9 communes. In the city master plan, this coverage will be extended to approximately 250 km^2, embracing the existing Vinh City, Cua Lo Town, and parts of the Nghi Loc and Hung Nguyen districts (see Figure 1).

According to the master plan, Vinh City will acquire the following roles.
First, it will lead the economic development of Northern and Central Vietnam. Second, it will become the center of education, science, culture and sports, and medical facilities. Third, it will become an industrial development center, and fourth, a role model of commercial and service sector development. Finally, it will become the hub and gate of transportation. These major foci will guide the development of Vinh City, and require both enhancement of existing urban

functions and the establishment of new ones.

This research assumes three patterns of land use on the basis of three perspectives: I) Development of Vinh City & Cua Lo Town, II) Connectivity of Vinh City and Cua Lo Town, and III) Expansion (additional area) of the urban area by approximately 60 km^2 (floor space) for future inhabitants. The impact of urbanization on the urban thermal and wind environment (temperature, humidity, and wind velocity) is assessed for three land use models; A) Co-development of Vinh City and Cua Lo Town, B) Intensive development of Vinh City, and C) Intensive development of Cua Lo Town.

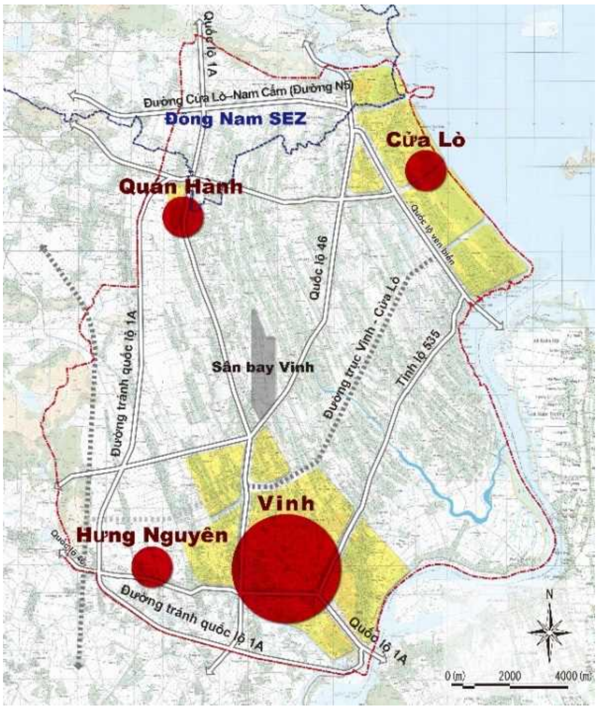

Figure 1 Current-situation map of the Vinh City vicinity

Outline of Simulations

To predict the thermal and wind environments in Vinh City, we applied the Weather Research and Forecasting (WRF) model (version 3.0.1.1). The WRF model is a state-of-the-art, globally used regional atmospheric model (fully compressible nonhydrostatic type) developed as a collaborative project among various American research organizations, including the National Center for Atmospheric Research (NCAR) and the National Centers for Environmental Prediction (NCEP). The WRF model can now be applied at various scales ranging from tens of meters to global dimensions, and is designed for both research and operational applications. It has two dynamics solvers, namely, the Advanced Research WRF (ARW) solver (Skamarock et al. 2008) and the Nonhydrostatic Mesoscale Model (NMM) solver. The ARW and NMM are mainly used in research and operation, respectively. The present study adopted the ARW dynamics solver, which provides several options of physical models. We selected the Mellor–Yamada–Janjic model (Janjic 1990; Janjic 2001) as the turbulence closure model (planetary boundary layer scheme), and the Noah–LSM (Chen and Dudhia 2001) as the land surface model. In urban areas, we also applied the urban canopy model (UCM) of Kusaka et al. (2001).

The WRF simulations were conducted on three nested computational domains (see Figure 2 and Table 1). The main computational domain was the smallest (Domain 3), with a horizontal grid resolution of 500 m. The zone enclosed by the rectangle in Domain 3 is the scope of the city master plan in Vinh City. Table 2 presents the simulated UCM cases. Seven cases were tested in this study. The target period was June 2011, as June is an especially hot month in Vietnam. The simulated cases differed in their land-use and urban parameters (average building height and green coverage ratio) in the city master plan area.

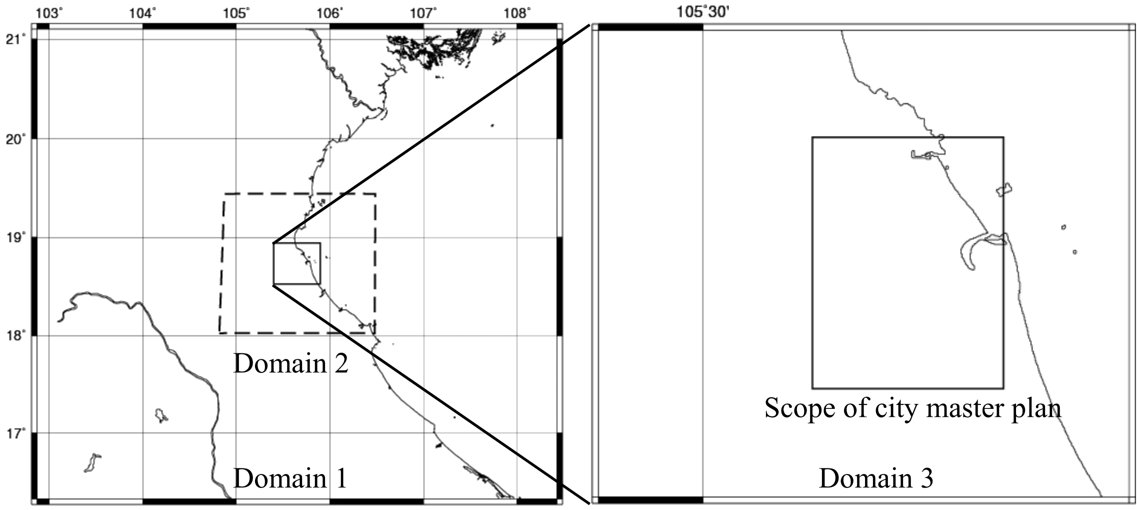

Figure 2 Computational domains

Table 1 Computational domain size and grid layout

Domain	Size	Grid points	Horizontal grid size
Domain 1	585 km × 540 km × 21 km	130 × 120 × 34	4.5 km
Domain 2	177 km × 159 km × 21 km	118 × 106 × 34	1.5 km
Domain 3	53 km × 47 km × 21 km	106 × 94 × 34	500 m

Table 2 Preconditions for the UCM

Urban area category	CBD			Existing urban district & areas occupied by a few urban facilities			New urban district		
Precondition	Building height (m)	Sky view factor (%)	Urban rate (%)	Building height (m)	Sky view factor (%)	Urban rate (%)	Building height (m)	Sky view factor (%)	Urban rate (%)
Case 0	-			12	37	70	-		
Case 1	26	20	50	12	37	70	12	37	70
Case 2									
Case 3									
Case 1′	26	20	50	12	37	70	12	37	40
Case 2′									
Case 3′									

Cases 0 and 1 represent the present land use (before urbanization; Figure 3) and the city master plan (after urbanization; Figure 4), respectively. In the city master plan (Case 1), the urban area increased from 107 km^2 to 138 km^2, with most of the urbanization implemented in the former irrigated cropland/pasture areas. The urban areas in Case 1 were classified into 1) central business district (CBD), 2) existing urban districts and areas occupied by a few urban facilities, and 3) new urban districts. In addition to Case 1, two centralized urban structure scenarios were introduced, representing intensive development in Vinh City and Cua Lo Town. Each scenario was modeled under a different land use pattern. In Case 2, most of the new urban districts were gathered in the northern part of the city master plan area (Figure 5), whereas in Case 3, they were clustered in the southern part (Figure 6).

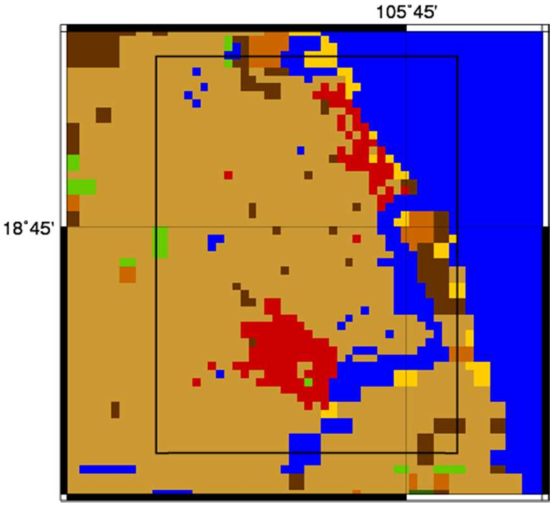

Figure 3 Case 0 (Present land use)

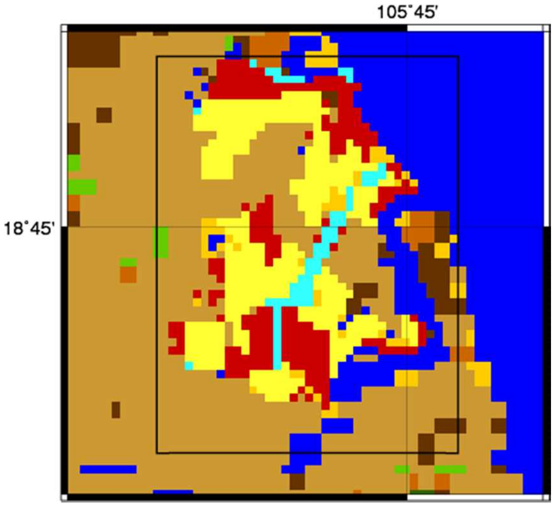

Figure 4 Case 1 (Land use model A)

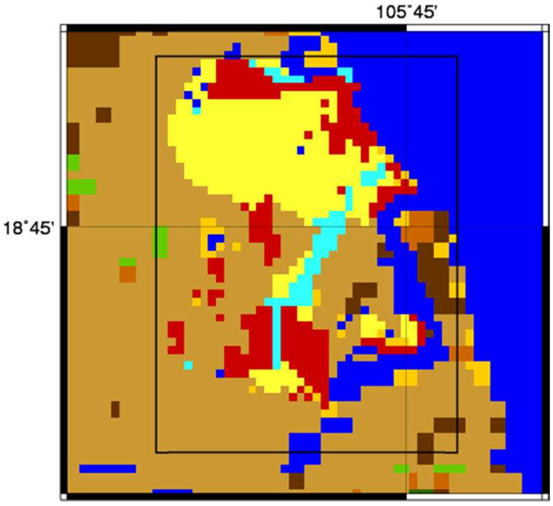

Figure 5 Case 2 (Land use model B)

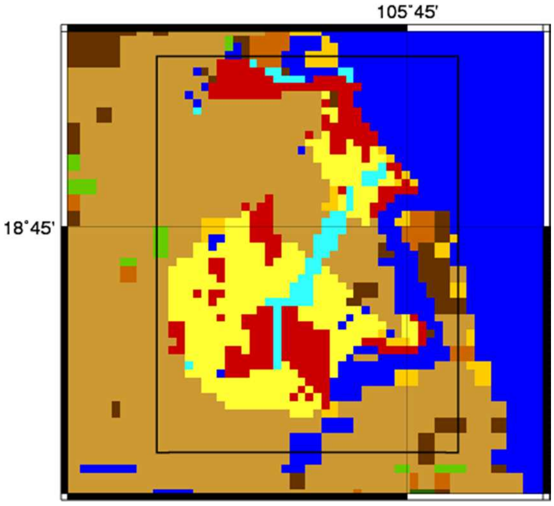

Figure 6 Case 3 (Land use model C)

Legend

- 🟫 Dryland Cropland and Pasture
- 🟫 Irrigated Cropland and Pasture
- 🟩 Cropland/Grassland Mosaic
- 🟫 Cropland/Woodland Mosaic
- 🟨 Grassland
- 🟧 Shrubland
- 🟩 Deciduous Broadleaf Forest
- 🟦 Water Bodies
- 🟦 CBD
- 🟥 Existing Urban District & areas occupied by a few urban facilities
- 🟨 New Urban District

Although the locations of the new urban districts differed between Cases 2 and 3, the total areal coverage of the new urban districts and the urban parameters were identical to those of Case 1. Furthermore, the effect of green coverage ratio in the new urban districts was evaluated in a further three cases (Cases 1′, 2′, and 3′). In these cases, the green coverage ratio was increased from 30% (urban coverage ratio = 70%) to 60% (urban coverage ratio = 40%), as shown in Table 2.

Because data on the anthropogenic heat release in the urban areas were unavailable, yet this parameter largely affects the urban thermal environment, the anthropogenic heat release was estimated as follows. The present power consumption per person in Vietnam is about one-eighth that in Japan (Nagoya metropolitan area) (Iizuka et al. 2011). Therefore, we assumed an anthropogenic heat release from the consumer sector in Vietnam of one-eighth that in Japan (Inoue et al. 2006). Considering the numbers and running efficiencies of cars and motorbikes in Hanoi City (a northern city in Vietnam like Vinh City) and Aichi Prefecture (Japan), the amount of anthropogenic heat released from the traffic sector was assumed as 10% that of Aichi Prefecture. From the above assumptions, the daily maximum anthropogenic heat release in Vinh City was set to 6 W/m^2. Moreover, the diurnal variation of anthropogenic heat release was estimated from the daily load (power demand) curve in Vietnam, and is plotted in Figure 7.

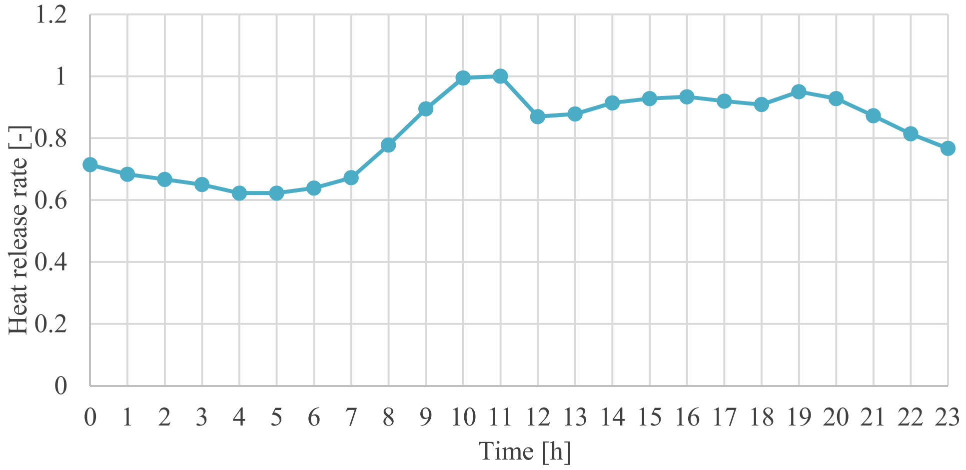

Figure 7 Diurnal variation of anthropogenic (consumer + traffic) heat release rate

Results and Discussion

The Case 0 temperature and wind velocity, and humidity at 2 pm, are shown in Figures 8 and 9 respectively. The temperature is lower in the northern sea area than in the south. Therefore, we can assume that the sea breeze blows towards the northern sea area. On the other hand,, the southern area (around the existing Vinh City) is subjected to winds from the Laos side. For analytical purposes, the master plan area was divided into areas north and south of 18° 45′ latitude, each with its distinct temperature characteristics. Figure 10 shows the monthly-averaged diurnal variations of the air temperature at 2 m above ground level in case 0 (for all areas, and for separate north and south areas). There is a 2.36 °C temperature difference between the north and south areas.

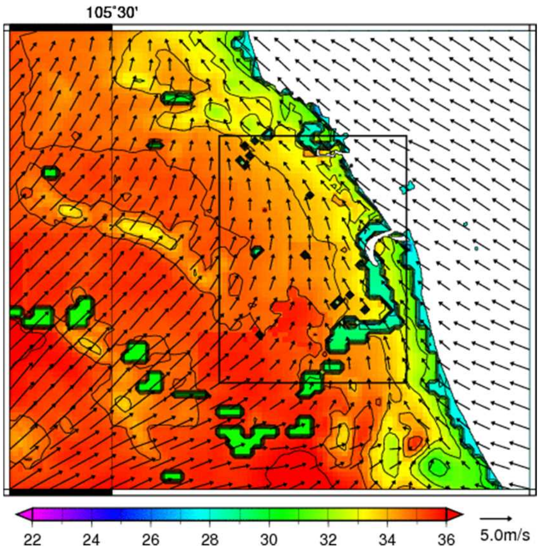

Figure 8 Temperature (°C) and wind velocity (m/s) in Case 0 at 2 pm

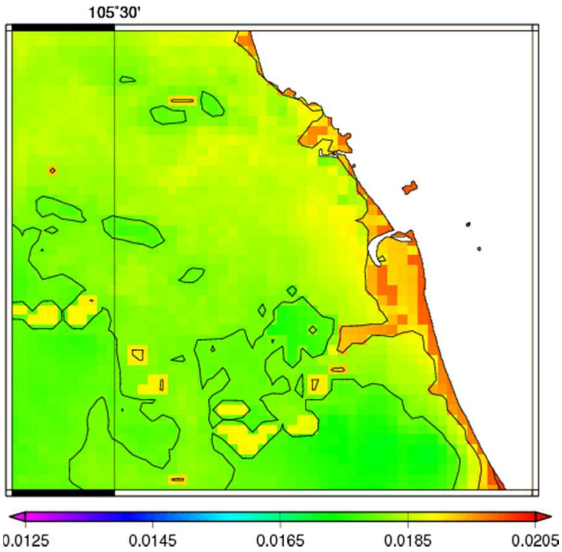

Figure 9 Absolute humidity (kg/kg) in Case 0 at 2 pm

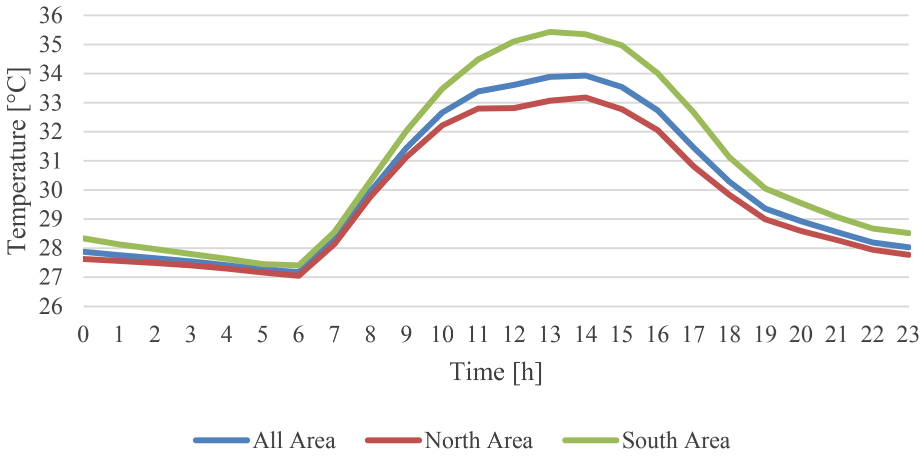

Figure 10 Diurnal variation of temperature differences between the north and south areas

Figures 11–13 illustrate the temperature differences between Case 0 and the urbanized cases (Cases 1, 2 and 3) at 2 pm in all areas. The differences in each plot indicate that temperature is significantly affected by land use. The temperature differences between Case 0 and the urbanized cases at 2 pm in the northern area are plotted in Figure 14. The maximum temperature increases from Case 0 in Cases 1, 2, and 3 are 0.71°C (at 12 pm (noon)), 1.05°C (at 2 pm), and 0.26°C (at 9 pm), respectively. Case 2 is not benefitted by the sea breeze effect, and its temperature rise is unrelated to inland northern area coverage. The maximum temperature difference (0.98°C at 3 pm) is found between Case 2 and Case 3. Unlike Case 2, the temperature rises in Cases 1 and 3 are proportional to the total coverage of northern areas. In Case 3, the temperatures are essentially unchanged by the urbanization (< 0.09°C change) from 7–11 am, and from 1 to 3 pm (a total of 8 hours). In the IPCC fifth assessment report (WGI AR5), they contributed an average temperature increase of 0.78°C between the 1850–1900 and 2003–2012 periods. Meanwhile, the 6 hours of unaltered temperature in Case 3 is an important factor in urbanization.

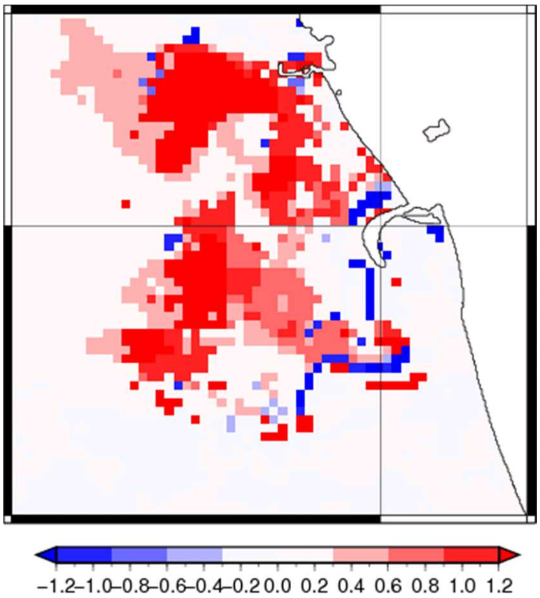

Figure 11 Temperature differences between Case 0 and Case 1 (°C)

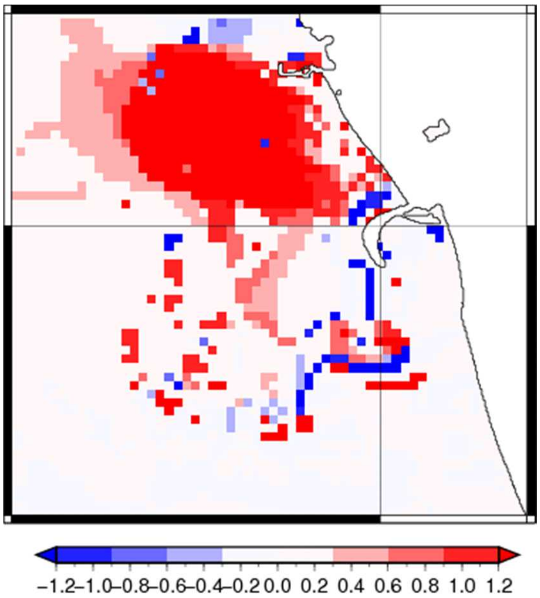

Figure 12 Temperature differences between Case 0 and Case 2 (°C)

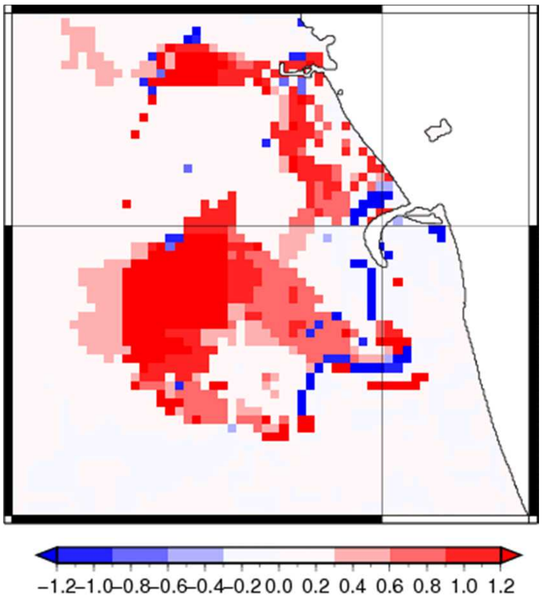

Figure 13 Temperature differences between Case 0 and Case 3 (°C)

Figure15 shows the temperature differences between Case 0 and the urbanized cases at 2 pm in the southern area. The maximum temperature increases from Case 0 in Cases 1, 2, and 3 are 1.63°C (at 12 pm), 1.48°C (at 12 pm), and 1.77°C (at 1 pm), respectively. The maximum temperature difference between Cases 2 and 3 (0.49°C at 6 pm) is half that of the northern part. Moreover, urbanization causes significant temperature change in all areas.

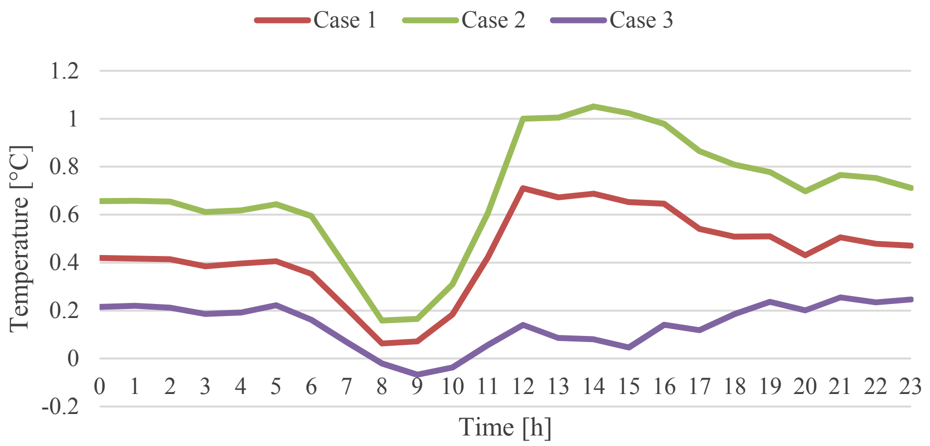

Figure14 Temperature differences between Case 0 and Cases 1, 2, and 3 at 2 pm in the northern area

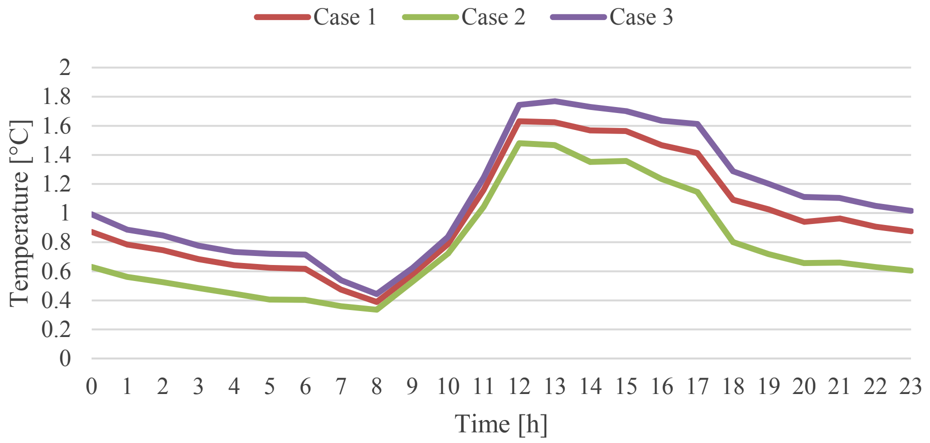

Figure 15 Temperature differences between Case 0 and Case 1, 2, and 3 at 2 pm in the southern area

Figures 16 and 17 show the temperature differences in each case when the urban coverage reduces from 70% to 40% (equivalently, the green coverage ratio increases from 30% to 60%). Results are plotted at 2 pm in the northern and southern areas. The maximum temperature decreases in the northern area are 0.32°C (Case 1→Case 1′ at 4 pm), 0.40°C (Case 2→Case 2′ at 3 pm), and 0.16°C (Case 3→Case 3′ at 4 pm). In the southern area, the maximum temperature decreases are 0.25°C (Case 1→Case 1′ at 5 pm), 0.09°C (Case 2→Case 2′ at 8 pm), and 0.29°C (Case 3→Case 3′ at 5 pm). Temperatures in the northern area are unchanged (<0.09°C change) between Cases 0 and 1′ from 7 to 10 am (4 hours) and between Cases 0 and 3′ from 7 am to 6 pm (12 hours). In Case 2′ in the northern area and all the southern area, the temperature change from Case 0 is always within 0.09°C, indicating that increasing the green coverage is ineffective.

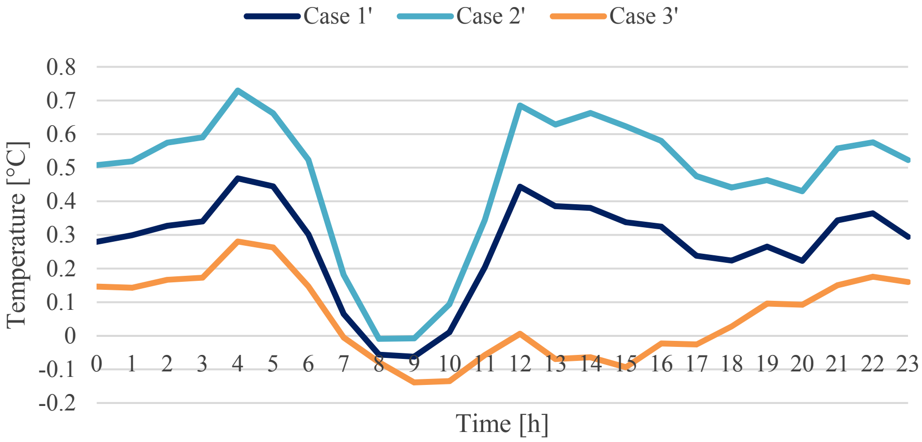

Figure 16 Temperature differences in each case when the urban rate is reduced from 70% to 40% at 2 pm in the northern area

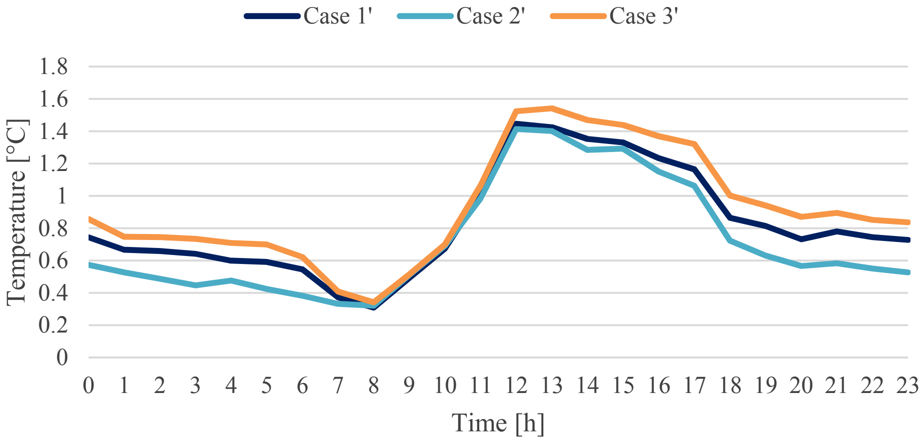

Figure 17 Temperature differences in each case when the urban rate is reduced from 70% to 40% at 2 pm in the southern area

The maximum temperature decrease across all areas (obtained by weighted average efficiency) are 0.28°C (Case 1→Case 1′ at 5 pm), 0.29°C (Case 2→Case 2′ at 4 pm), and 0.24°C (Case 3→Case 3′ at 5 pm). Therefore, although green coverage affects the temperature in the independent north and south areas, it exerts negligible effect across the whole area.

Establishment of the city master plan requires co-development of Vinh City and Cua Lo Town. The most impartial temperature effect (with respect to increase or decrease) is obtained under Case 1 or Case 1′ land use. Other land uses reduce the temperature in the northern or southern area, but not in both areas. Therefore, implementing these patterns would unbalance the environmental control.

By comprehending the urban thermal and wind environments in advance, we can set priorities for land use. Thus, industrial zones should be erected in regions of small air temperature change, while nice sea breezes could be exploited for resort areas.

Conclusions

Using the WRF model, we verified the effects of land use pattern on urban thermal and wind environments in an expanding city in Vietnam. When the area was divided into northern and southern parts, urbanization always led to increased temperature. The effect of green coverage ratio in each land use pattern was also evaluated.

In the co-development between Vinh City and Cua Lo Town, we should maximize the temperature impartiality between the northern and southern areas. To this end, we should adopt a Case 1 or Case 1′ land use.

The 250 km^2 study area has an unusual climatic mix of sea breeze and wind from the Laos side. To establish a comprehensive city master plan, we must examine urban structures and locations at other sites, and collect knowledge from other case studies.

Acknowledgments

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