Environmental impact assessment of introducing compact city models by downscaling simulations

Abstract

In this study, first, three compact city models with different degrees of compactness for a prefecture in a large metropolitan area of Japan were designed. Based on the urban classifications "population-induced area," "population-unchanged area," and "withdrawal area," we constructed the compact city models. Next, the impact of introducing the designed compact city models on the summer thermal environment in the 2050s was quantitatively assessed by downscaling simulations from a global scale to an urban scale. Moreover, we examined the effect of a land use change in the withdrawal area on the future thermal environment in the urban area (the population-induced and population-unchanged areas). As expected, a temperature increase in the urban area occurred due to urban densification in the compact city models. On the other hand, the temperature decrease in the urban area as a result of changing the land use of the withdrawal area, i.e., by replacing the withdrawal area with grassland, approximately offset the above-mentioned temperature increase. This implies that, in compact city planning, it is necessary to properly plan not only for the concentrated urban area but also for treatment of the withdrawal area from the viewpoint of environmental impact.

Keywords

Compact city model; Environmental impact assessment; Urban thermal environment; Future projection; Downscaling simulation

1. Introduction

As stated in a UN population report (United Nations, 2019), the world's population continues to grow. On the other hand, some cities, mostly Asian and European cities in low-fertility countries, have experienced population decline in recent years (United Nations, 2018, 2019). Moreover, in developed countries, such as Europe, the United States, and Japan, many cities are shrinking (Blanco et al., 2009), and those cities are experiencing or have recently experienced declines in both population and economic production over the past decades (Schwarz et al., 2018). Population decline due to low birth rate is one of the major social problems in Japan (e.g., Tamura et al., 2018). Japan's population has entered a long-term reduction process, peaking at about 128 million in 2010, and is projected to decline by about 20% by 2050 (National Institute of Population and Social Security Research, 2017).

Due to the declining population and severe financial situation, compact city planning has recently attracted much attention in Japan as one of the measures for the sustainability of cities (e.g., Makido et al., 2012; Koike, 2014; Hasegawa et al., 2019). The term "compact city" was first advocated by Dantzig and Saaty (1973). According to an OECD report (2012), the key characteristics of a compact city are (1) dense and proximate development patterns, (2) urban areas linked by public transport systems, and (3) accessibility to local services and jobs. Compact city planning has various merits, such as prevention of urban expansion and sprawl, improvement of accessibility to public and living service facilities, and breakaway from car-dependent societies (Burton, 2000).

Conversely, some demerits have been pointed out in compact city planning (e.g., Breheny, 1997; Burton, 2000; Gaigné et al., 2012). Breheny (1997) mentioned that compact city planning is remarkably radical, given the free market ideology, and raised the doubts about the economic, technical, and political prospects of compact city planning from the viewpoint of feasibility. Burton (2000) summarized the benefits and drawbacks of compact city planning from the viewpoint of social equity. The author argued that the main drawbacks are likely to be reduced living space and a lack of affordable housing. There have been many discussions about the low proportion of green spaces in compact city planning (e.g., Jim, 2004; Tang et al., 2007; Fuller & Gaston, 2009; Haaland & van den Bosch, 2015; Tappert et al., 2018; Artmann et al., 2019), and some approaches to "compact and green" city planning have been examined (e.g., Artmann et al., 2019; Hansen et al., 2019).

Greening has many functions, and one of them is the impact on urban climates (e.g., Oliveira et al., 2011; Ng et al., 2012; Tsoka et al., 2018; Bartesaghi Koc et al., 2018). The latent heat of vaporization associated with transpiration suppresses the rises in urban surface temperature and air temperature. At the same time, however, we should beware of the increase in humidity (e.g., Zhang et al., 2013). Under hot and humid environments, such as those in East and Southeast Asian countries (especially in the future, with the progress of global warming (IPCC, 2014)), a further increase in humidity will diminish human comfort and is likely to cause health damage, such as heatstroke.

Regarding the impact on urban climates, basically, urban densification in compact city planning will lead to heat concentration and thus create a more localized heat island phenomenon. However, introducing area energy management such as regional energy use and interchange will help to mitigate this problem.

Although compact city planning is being discussed all over the world (e.g., Stevenson et al. 2016; Giridharan & Emmanuel, 2018; Lee & Lim, 2018; Sakamoto et al., 2018; Mouratidis, 2019), no common or single best solution exists. Planning according to geographical, climatic, social, economic, historical, and cultural characteristics is required. In addition, we should carefully consider target spatial and temporal scales for compact city planning. In Japan, the Ministry of Land, Infrastructure, Transport and Tourism proactively promotes compact city planning (MLIT, 2019). As mentioned above, the declining population and severe financial situation are the main reasons compact city planning is needed in Japan, and this situation is a little different from those driving the need for compact city planning in other parts of the world.

Under these circumstances, many local governments in Japan have proposed their own compact city plans. However, their target spatial scales are very local, and there are no comprehensive plans on a wider spatial scale, i.e., on prefecture or metropolitan-area scale. If the local compact city plans of neighboring local governments are combined, it may result in a disorderly sparse city plan on a wider scale. Moreover, in the declining population and severe financial situation, competition for population acquisition may occur between the neighboring local governments. Comprehensive control on a wider scale will be required, even if very localized compact city plans are considered.

We have tackled with the quantitative impact assessment of compact city planning for the Nagoya metropolitan area in Japan on the urban thermal environment (Iizuka et al., 2012; 2014). The compact city planning introduced in our previous studies was simple and made by a simple change of the locations of urban areas considering a population decrease. Introducing more sophisticated planning, Lemonsu et al. (2015), Kusaka et al. (2016), and Yang et al. (2016) conducted the environmental impact assessment of compact city planning in Paris (France), Tokyo (Japan), and Beijing (China), respectively. As described below, the main purpose of this study was to assess the impact of introducing sophisticated and unique compact city models on the urban thermal environment.

In this study, we first designed three compact city models on a wider spatial scale (Aichi Prefecture in the Nagoya metropolitan area) in which the degrees of compactness were different, based on the urban classifications “population-induced area,” “population-unchanged area,” and “withdrawal area.” Next, we quantitatively evaluated the impact of introducing the three compact city models on the summer thermal environment in the future (the 2050s) using a numerical technique called “downscaling simulation” (e.g., Iizuka, 2018). We also examined the effect of a land use change in the withdrawal area on the future thermal environment in the urban area (the population-induced and population-unchanged areas).

2. Outline of designed compact city models

Three compact city models for Aichi Prefecture were designed in this study. Aichi Prefecture is the largest and core prefecture in the Nagoya metropolitan area (the third largest metropolitan area in Japan). The area and population of Aichi Prefecture are 5172 km^2 and 7.55 million (as of March 2020), respectively. The prefectural capital is the city of Nagoya, with a population of 2.32 million (as of April 2020).

All three compact city models were constructed based on the urban classifications "population-induced area," "population-unchanged area," and "withdrawal area," although they have different degrees of compactness. The spatial resolution of the designed compact city models was 1 km × 1 km and was the same as the horizontal resolution of the smallest domain of downscaling simulations conducted in this study (cf. Chapter 3). Moreover, in all compact city models, the areas other than the urban area were set to be the same as the present land use.

2.1. Assessment items for urban classification

The urban classification was performed based on the current assessments of (1) natural disaster risks, (2) substantiality of public transportation, (3) substantiality of public service facilities, and (4) substantiality of living service facilities.

2.1.1. Natural disaster risks

For the assessment of natural disaster risks, we considered the risk of earthquakes, tsunamis, and sediment disasters. A Japanese governmental organization, Headquarters for Earthquake Research Promotion (2020), reported a probability of 70–80% that a huge earthquake called the Nankai Trough Earthquake will occur in a wide region, including Aichi Prefecture, within 30 years. In this region, disaster mitigation/prevention efforts against the earthquake and subsequent disasters, such as a tsunami, are very important.

Based on simulated data on the maximum seismic intensity and the maximum inundation depth due to tsunami reported by Aichi Prefecture (2014) and the sediment disaster warning area data provided by the National Land Numerical Information download service (2017), we divided the urban areas into two categories: "safe" and "dangerous." Here, an urban area was considered safe if all of the following conditions were satisfied:

Condition 1: The maximum seismic intensity was less than 7.

Condition 2: The maximum inundation depth was less than 2 m.

Condition 3: The sediment disaster warning area was less than 70%.

2.1.2. Substantiality of public transportation

We assessed the substantiality of public transportation based on the distance from a train station to a living area. Here, three levels were set as follows:

Level 0: The distance from a station was more than 1500 m.

Level 1: The distance from a station was more than 800 m and less than or equal to 1500 m.

Level 2: The distance from a station was less than or equal to 800 m.

In future city planning, the city of Nagoya (2009) defined an area within a radius of 800 m from a train station as a convenient living area.

2.1.3. Substantiality of public service facilities

The substantiality of public service facilities was assessed based on the distance from a living area to a facility and the number of facilities available. However, note that the type of facilities was not considered here. Four levels were set as follows:

Level 0: There are no public service facilities with a total floor area of 1000 m^2 or more within a radius of 2 km.

Level 1: There are one or two public service facilities with a total floor area of 1000 m^2 or more within a radius of 2 km.

Level 2: There are three public service facilities with a total floor area of 1000 m^2 or more within a radius of 2 km.

Level 3: There are four or more public service facilities with a total floor area of 1000 m^2 or more within a radius of 2 km.

2.1.4. Substantiality of living service facilities

We assessed the substantiality of living service facilities based on accessibility to grocery stores, hospitals, and financial institutions. Accessibility was quantitatively evaluated using a score method proposed by Takewaki et al. (2017). The score for each accessibility, to grocery stores, hospitals, and financial institutions, was calculated using an accessibility value weighted according to the distance from a living area to each type of facility and an expected appearance value given according to the area covered by one of each type of facility. A higher score indicates better accessibility. Here, four levels were set as follows:

Level 0: The total score is very low (less than 0.7).

Level 1: The total score is low (0.7–1.3).

Level 2: The total score is medium (1.4–2.0).

Level 3: The total score is high (2.1 or higher).

2.2. Compacting method and urban classification

Using the assessment items described in Section 2.1, three compact city models, each with a low, medium, or high degree of compactness, were constructed in this study.

In the model with a low degree of compactness (hereafter the Low-CC model), the population-induced area was “safe” with regard to natural disaster risks and had a rating of Level 1 or higher in both public and living service facility substantiality assessments. On the other hand, an urban area where the assessment of natural disaster risks was “dangerous” or all substantiality assessments of public transportation, public service facilities, and living service facilities were Level 0 was designed as a withdrawal area. The remaining urban area was assumed to be a population-unchanged area.

In the model with a medium degree of compactness (hereafter the Medium-CC model), the population-induced area was “safe” with regard to natural disaster risks, and had a rating of Level 1 or higher in the public transportation substantiality assessment and a rating of Level 2 or higher in both public and living service facility assessments. On the other hand, an urban area where the assessment of natural disaster risks was “dangerous” or both public and living service facility substantiality assessments were Level 1 or lower was designed as a withdrawal area. The remaining urban area was assumed to be a population-unchanged area.

In the model with a high degree of compactness (hereafter the High-CC model), the population-induced area had a rating of Level 3 or higher in the public or living service facility substantiality assessment in addition to a “safe” rating for natural disaster risks and a rating of Level 2 or higher in the public transportation substantiality assessment. On the other hand, an urban area where the assessment of natural disaster risks was “dangerous” or both public and living service facility substantiality assessments were Level 2 or lower was designed as a withdrawal area. The remaining urban area was assumed to be a population-unchanged area.

Fig. 1(1) shows the urban area (blue) of the present land use. Fig. 1(2)–(4) illustrates the designed compact city models with low, medium, and high degrees of compactness, respectively. The Low-CC model (Fig. 1(2)) corresponded to a plan that treated many municipalities as the hubs for compacting. The Medium-CC model (Fig. 1(3)) was intended for a plan that treated representative local cities as the hubs for compacting. The High-CC model (Fig. 1(4)) was close to a compact city plan concentrated in a large city (the city of Nagoya).

In all compact city models, we assumed that the total population in the withdrawal area moved equally to each population-induced area. Regarding the withdrawal area, two cases were considered. One was a case in which the withdrawal area was not changed, namely, the vacant buildings in the area remained. The other was a case in which the withdrawal area was replaced with grassland.

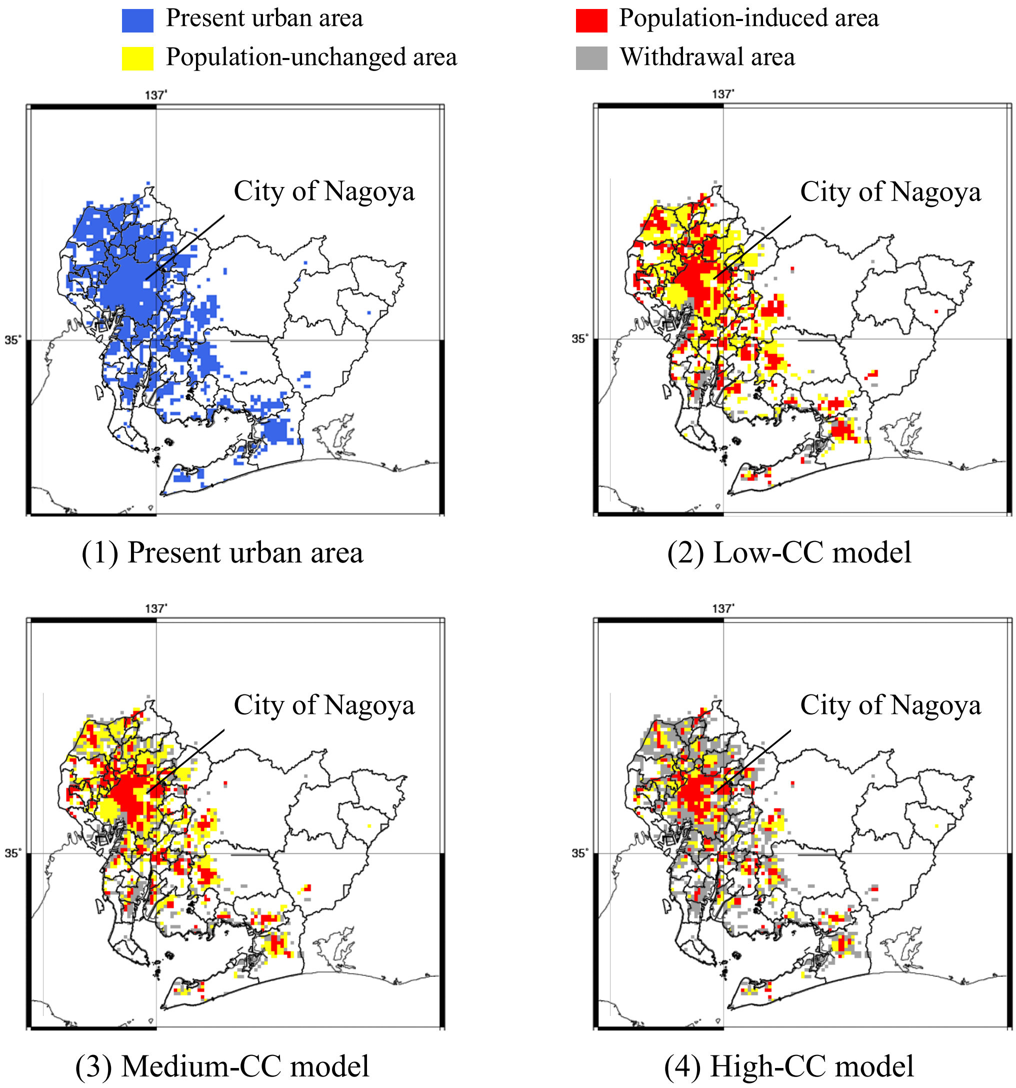


Fig. 1. Present urban area and compact city models.

3. Outline of downscaling simulations

The main purpose of this study was to assess the impact of introducing the designed compact city models (cf. Chapter 2) on the urban thermal environment, especially on a future thermal environment. The impact assessment was conducted by using a dynamical downscaling simulation technique (e.g., Wang et al., 2004; Kusaka et al., 2012; Kikumoto et al., 2015; Iizuka et al., 2015; Lee et al., 2017; Iizuka, 2018; Iizuka et al., 2018; Doan et al., 2019) from a global scale to an urban scale. The period targeted in the downscaling simulations was the summer (the month of August) of the 2050s. For comparison, a downscaling simulation without introducing the compact city models, i.e., with the present urban form, for the summer of 2010 was also performed.

3.1. Simulation method and models

For the future (the 2050s) projections conducted in this study, a pseudo global warming method proposed by Kimura & Kitoh (2007) was introduced to perform downscaling from the results of a general circulation model (GCM) on a global scale to a regional climate model (RCM) on smaller spatial scales. In their method, GCM results are not used directly for downscaling. The linear coupling of the differences between future and present climatic elements simulated by a GCM and reanalysis data, i.e., pseudo global warming data, is given to an RCM.

A direct downscaling method is simple, but one of the drawbacks is that the bias of the selected GCM results is directly downscaled to an RCM. On the other hand, in the pseudo global warming method, the bias can be removed or mitigated because the downscaled data to an RCM are based on not GCM results themselves but the climatic differences. However, the non-linear effect between urban induced warming and global climate change cannot be considered by the pseudo global warming method. Namely, in the method, the impact of urban induced warming under current climates is almost the same as that under future climates. In contrast, the non-linear effect can be captured by direct downscaling simulations (e.g., Krayenhoff et al., 2018).

In this study, we adopted present and future GCM results simulated by GFDL-CM3 (Donner et al., 2011) and the model with RCP8.5 (van Vuuren et al., 2011). RCP8.5 is a future greenhouse gas emissions scenario and is the most serious scenario for the future progress of global warming among the representative concentration pathways (RCPs). Horizontal winds, potential temperature, geopotential height, sea surface temperature, and ground surface temperature were used as the future and present climatic elements in creating the pseudo global warming data. The future climatic elements were the 10-year average values of the 2050s, and the present ones were the 10-year average values of the 2000s. We used the NCEP FNL Operational Model Global Tropospheric Analyses data for August 2010 (https://rda.ucar.edu/datasets/ds083.2/) as the reanalysis data. Actually, in Japan, it was extremely hot in August 2010 (http://ds.data.jma.go.jp/tcc/tcc/news/press_20100910.pdf). The reason why we selected the unordinary circumstance as the year of the reanalysis data was to investigate the impacts on human health damage and building cooling loads (especially the peak cooling loads) under the most serious possible future condition in the next phase of this study. For the same reason, we chose RCP8.5, which is the most serious scenario among RCPs, as the future greenhouse gas emissions scenario.

As the RCM for downscaling simulations, we adopted the Weather Research and Forecasting (WRF) model (Skamarock et al., 2008). Three nested domains (Domains 1–3) were used for the WRF model, as shown in Fig. 2. The smallest domain (Domain 3) was the main computational domain. The sizes and horizontal grid resolutions of Domains 1–3 were 1975 km × 1975 km × 20 km and 25 km, 500 km × 500 km × 20 km and 5 km, and 120 km × 120 km × 20 km and 1 km, respectively. The above-mentioned pseudo global warming data were applied for the initial and boundary conditions for the WRF model, i.e., the initial conditions of all domains and the boundary conditions of Domain 1.

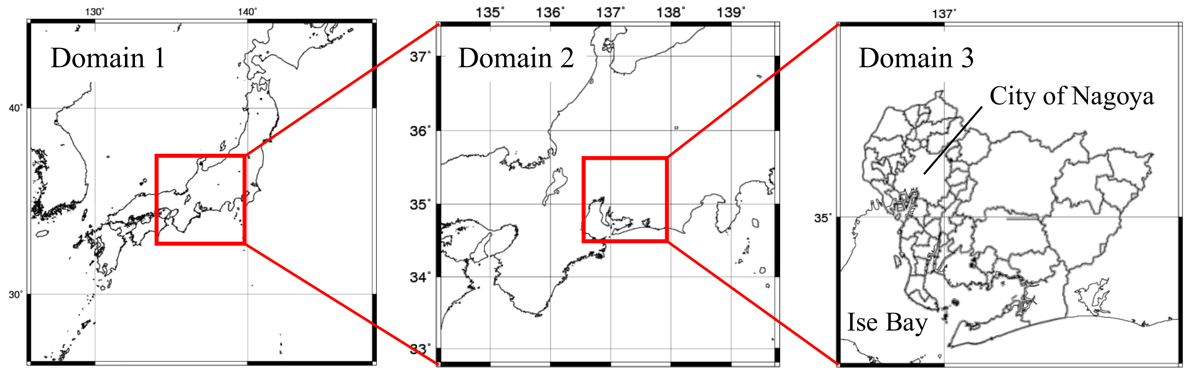


Fig. 2. Nested domains for the WRF model.

3.2. The urban canopy model and its parameterizations

In RCMs, in which buildings and structures in urban areas cannot be directly resolved, an urban canopy model is often introduced to reproduce the environmental impact of urban areas. In this study, we introduced an urban canopy model proposed by Kusaka et al. (2001) in Domain 3 of the WRF model.

The urban classifications "population-induced area," "population-unchanged area," and "withdrawal area" for constructing the three compact city models (cf. Chapter 2) were considered by changing two parameters of the urban canopy model, i.e., the average height of buildings and the amount of anthropogenic heat release. In the population-unchanged area, the values used in the present urban area (average height of buildings: 9.0 m; amount of anthropogenic heat release: 15.0 W/m^2) were applied as those parameters. As described in Section 2.2, the total population in the withdrawal area moved equally to each population-induced area; therefore, in the population-induced area, the effects of the increase in population were expressed by increasing the average height of buildings and the amount of anthropogenic heat release. Table 1 shows the average height of buildings and the amount of anthropogenic heat release for the urban classification of each compact city model.

Table 1. Average height of buildings and amount of anthropogenic heat release for the urban classification of each compact city model.

Compact city model	Urban classification	Average height of buildings [m]	Amount of anthropogenic heat release [W/m^2]
Low-CC	Population-induced area	12.8	21.3
	Population-unchanged area	9.0	15.0
	Withdrawal area with vacant buildings	9.0	0.0
Medium-CC	Population-induced area	19.3	32.2
	Population-unchanged area	9.0	15.0
	Withdrawal area with vacant buildings	9.0	0.0
High-CC	Population-induced area	38.3	63.8
	Population-unchanged area	9.0	15.0
	Withdrawal area with vacant buildings	9.0	0.0

3.3. Simulated cases

Eight cases were simulated, as shown in Table 2.

Table 2. Simulated cases.

	Target period	Urban form	Treatment of the withdrawal area
Case 0	August 2010	Present	–
Case 1	August in the 2050s	Present	–
Case 2-1		Low-CC model	No change; vacant buildings remained
Case 2-2			Replaced with grassland
Case 3-1		Medium-CC model	No change; vacant buildings remained
Case 3-2			Replaced with grassland
Case 4-1		High-CC model	No change; vacant buildings remained
Case 4-2			Replaced with grassland

4. Results and discussion

4.1. Verification of the prediction accuracy

First of all, verification of the prediction accuracy of the simulation model used is essential. Fig. 3 compares the monthly averaged (for August 2010) diurnal variations of air temperature at the location of the meteorological observatory in the city of Nagoya (at the mesh including the observatory) between the observation data at a height of 1.5 m and the simulation result of

Case 0 at a height of 2 m. Although the simulated temperature is slightly lower than the observation data for the entire time, the correspondence with the observation data is quite good. The average value of the temperature difference over time, namely, the monthly averaged (for August 2010) temperature difference, is 0.34 °C.

Needless to say, it is impossible for the simulation model, in which buildings and structures in urban areas cannot be directly resolved and an urban canopy model is introduced instead, to perfectly reproduce the observation data. It may be possible to further improve the correspondence with the observation data by finely adjusting the parameterizations of the urban canopy model; however, we judged that the prediction accuracy of the simulation model used in this study is sufficient.

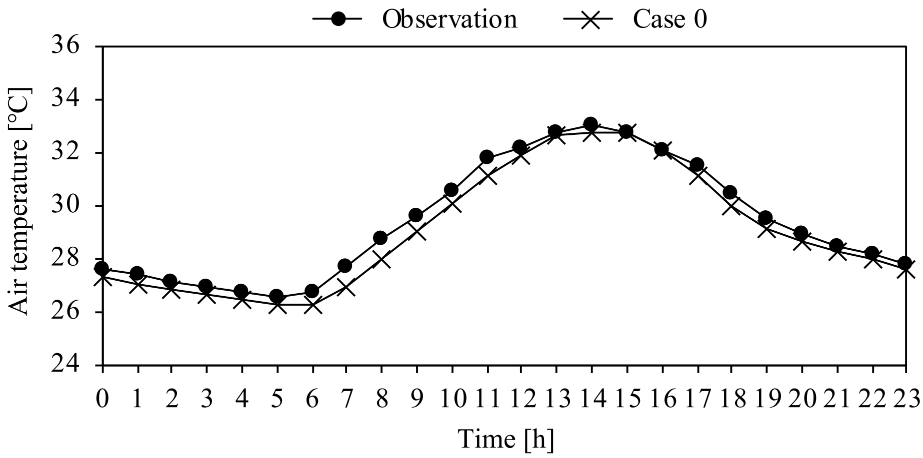
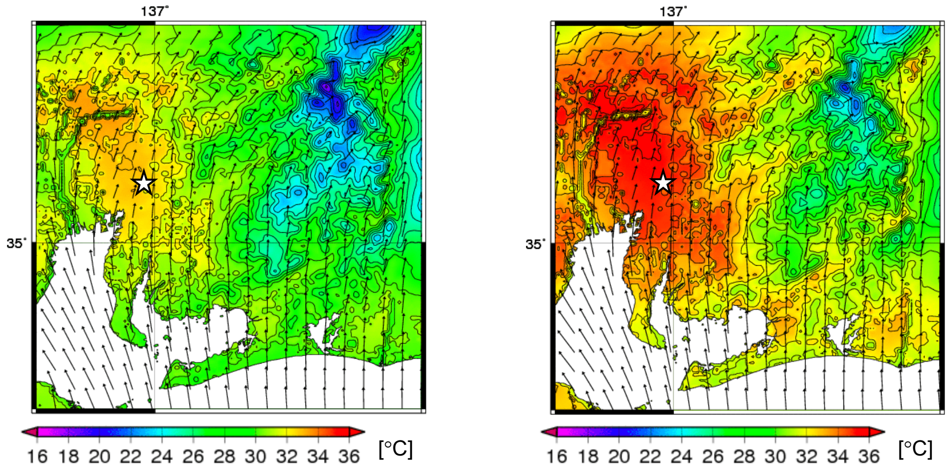


Fig. 3. Monthly averaged diurnal variations of air temperature at the location of the meteorological observatory in the city of Nagoya.

4.2. Impact of the future progress of global warming

Before discussing the environmental impact of introducing the compact city models designed in this study, the impact of the future progress of global warming on the urban thermal environment is assessed by comparing Case 0 (August 2010, present urban form) and Case 1 (August in the 2050s, present urban form). Fig. 4 compares the horizontal distributions of the monthly averaged (for the month of August) air temperature at a height of 2 m and velocity vectors at a height of 10 m at 3 p.m. in Domain 3. (The stars in Fig. 4 denote the central part of the city of Nagoya.) A remarkable heat island phenomenon is formed around the city of Nagoya in both cases. However, the heat island in Case 1 is hotter and more serious than that in Case 0.



(1) Case 0 (August 2010) (2) Case 1 (August in the 2050s)

Fig. 4. Horizontal distributions of the monthly averaged air temperature at a height of 2 m and velocity vectors at a height of 10 m at 3 p.m.

Fig. 5 compares the space-averaged (over the whole urban area in Domain 3) and monthly averaged (for the month of August) diurnal variations of air temperature at a height of 2 m between Case 0 and Case 1. For the entire time, the temperature in Case 1 is 2.5–2.8 °C higher than that in Case 0. The temperature difference shows the impact of the future (the 2050s) progress of global warming on the urban thermal environment. However, note that the temperature difference varies depending on which GCM results we use and which future scenarios, such as the greenhouse gas emissions scenario, we select. The variation is called uncertainty in future projections. In the next phase of this study, we will perform a multimodel ensemble analysis and a multiscenario ensemble analysis to assess the ranges of uncertainty.

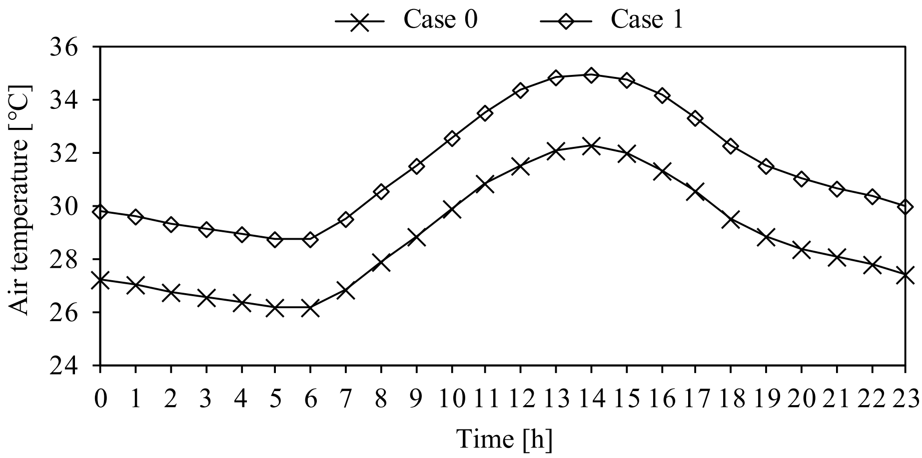


Fig. 5. Space-averaged and monthly averaged diurnal variations of air temperature at a height of 2 m.

4.3. Impact of the introduction of compact city models

As described in Section 2.2 and Table 2 (Section 3.3), two treatments of the withdrawal area in each compact city model, i.e., no change with vacant buildings remaining and replacement with grassland, were considered in this study. In this section, we discuss the results of Case X-1, in which the withdrawal area was not changed and vacant buildings remained.

Fig. 6 shows the space-averaged (over the whole urban area in Domain 3) and monthly averaged (for the month of August) diurnal variations of the difference in air temperature at a height of 2 m between Case X-1 (August in the 2050s, each compact city model) and Case 1 (August in the 2050s, present urban form). Here, note that the whole urban area in each compact city model means the total of the population-induced and population-unchanged areas. The average values of those temperature differences over time, namely, the monthly averaged temperature differences, are 0.12 °C for Case 2-1 (Low-CC model) minus Case 1, 0.19 °C for Case 3-1 (Medium-CC model) minus Case 1, and 0.34 °C for Case 4-1 (High-CC model) minus Case 1. The maximum temperature increases from Case 1 are 0.21 °C for Case 2-1 (4 p.m.), 0.29 °C for Case 3-1 (5 p.m.), and 0.57 °C for Case 4-1 (6 p.m.).

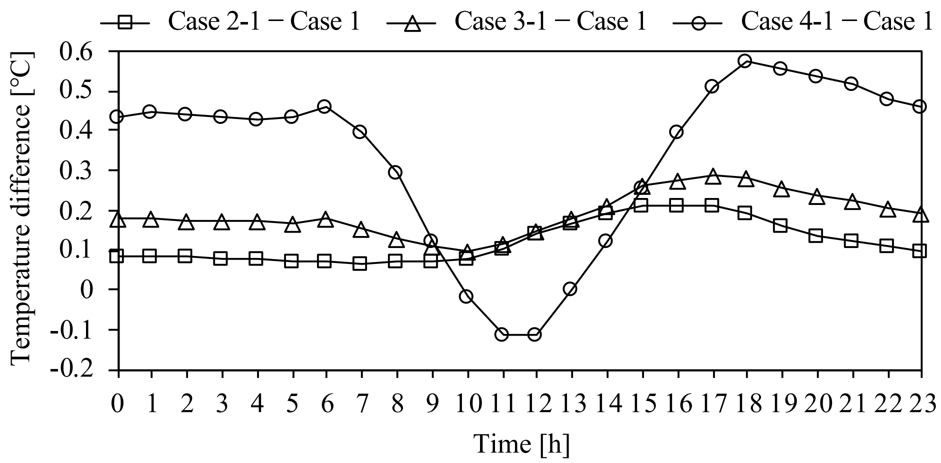


Fig. 6. Space-averaged and monthly averaged diurnal variations of the difference in air temperature at a height of 2 m between Case X-1 and Case 1.

The results shown in Fig. 6 are considered as an example of the demerit of introducing compact city planning from the viewpoint of environmental impact, namely, the formation of a more localized heat island phenomenon, as pointed out in Chapter 1. Focusing on the monthly averaged temperature differences and the maximum temperature increases in Fig. 6, the demerit becomes worse as the degree of compactness increases.

On the other hand, the diurnal variation of the temperature difference from Case 1 (present urban form) fluctuates greatly in Case 4-1 (High-CC model). This is mainly due to the greater heat capacity in the urban area of Case 4-1. In Case 4-1, the heat capacity in the urban area increases by the considerably increased average height of buildings in the population-induced area (cf. Table 1). The greater the heat capacity is, the harder it is to quickly warm up and quickly cool down the urban area. Therefore, from morning to around midday, the temperature difference between Case 4-1 and Case 1 becomes smaller due to the thermal property of being hard to quickly warm up the urban area in Case 4-1. In contrast, from night to early morning, the temperature difference becomes larger due to the thermal property of being hard to quickly cool down the urban area in Case 4-1.

4.4. Impact of the treatment of the withdrawal area in compact city planning

In this section, we discuss the impact of different treatments of the withdrawal area in each compact city model, i.e., the impact of the difference between Case X-1 (no change) and Case X-2 (replacement with grassland).

Fig. 7 shows the space-averaged (over the whole urban area in Domain 3) and monthly averaged (for the month of August) diurnal variations of the difference in air temperature at a height of 2 m between Case X-2 and Case X-1. For the entire time, the temperature in Case X-2 is lower than that in Case X-1. The average values of those temperature differences over time, namely, the monthly averaged temperature differences, are -0.09 °C for Case 2-2 minus Case 2-1 (Low-CC model), -0.18 °C for Case 3-2 minus Case 3-1 (Medium-CC model), and -0.38 °C for Case 4-2 minus Case 4-1 (High-CC model). The maximum temperature decreases from Case X-1 are -0.14 °C for Case 2-2 (6 p.m.), -0.25 °C for Case 3-2 (6 p.m.), and -0.50 °C for Case 4-2 (1 a.m.).

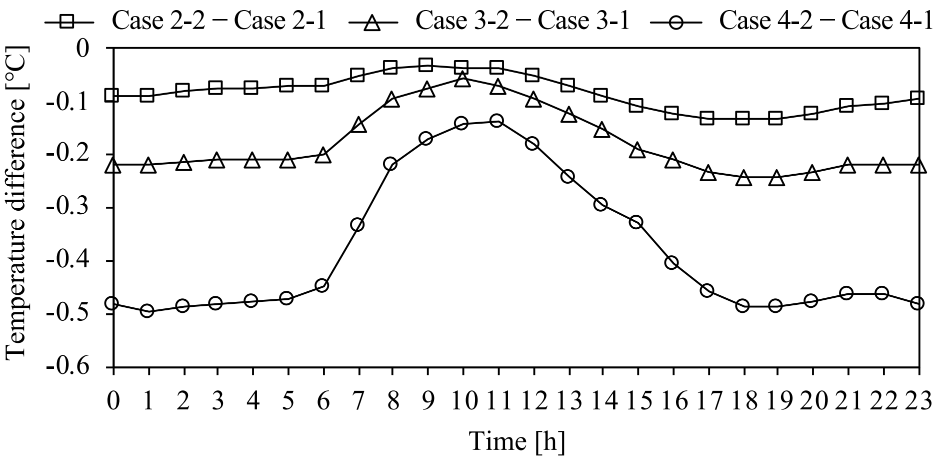
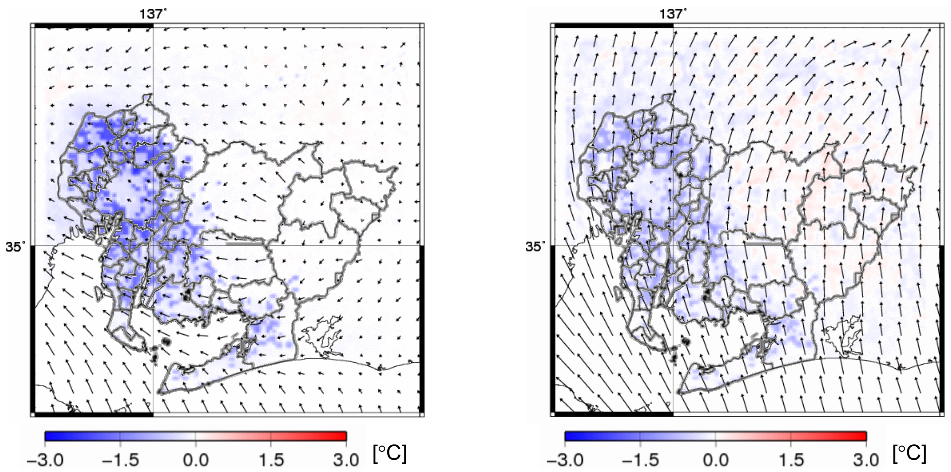


Fig. 7. Space-averaged and monthly averaged diurnal variations of the difference in air temperature at a height of 2 m between Case X-2 and Case X-1.

Those temperature decreases in the urban area of Case X-2 are caused mainly by the advection effect of lower-temperature air from the withdrawal area (grassland). As an example, the horizontal distributions of the monthly averaged (for the month of August) temperature difference at a height of 2 m between Case 4-2 and Case 4-1 and velocity vectors at a height of 10 m for Case 4-2 at 3 a.m. and 12 p.m. in Domain 3 are illustrated in Fig. 8. We can clearly observe that the air cooled in the withdrawal area (grassland; cf. Fig. 1(4)) flows into the urban area (the population-induced and population-unchanged areas) along the wind direction.



(1) 3 a.m. (August in the 2050s) (2) 12 p.m. (August in the 2050s)

Fig. 8. Horizontal distributions of the monthly averaged temperature difference at a height of 2 m between Case 4-2 and Case 4-1 and velocity vectors at a height of 10 m for Case 4-2.

Furthermore, as a whole, the temperature decreases in the urban area of Case X-2 are small during the daytime and large from night to early morning, as shown in Fig. 7. This is mainly due to the thermal properties of the cases with and without land use change in the withdrawal area. During the daytime, in Case X-2, the withdrawal area changed to grassland is comparably easily warmed up due to its relatively low heat capacity, and thus the air that is not cool enough flows into the urban area. On the other hand, in Case X-1, the withdrawal area where vacant buildings remain is comparably hardly warmed up due to its relatively high heat capacity, and thus the air that is not very hot flows into the urban area during the daytime. As a result, the temperature differences between Case X-2 and Case X-1 become relatively small during that period. From night to early morning, in Case X-2, the withdrawal area changed to grassland is comparably easily cooled down, and thus the cooler air flows into the urban area. Conversely, in Case X-1, the withdrawal area without change is comparably hardly cooled down, and thus the air that is not cool enough (but is of course not warm) flows into the urban area from night to early morning. As a result, the temperature differences between Case X-2 and Case X-1 become relatively large during that period.

The comparison of the results in Figs. 6 and 7 is very interesting and reveals an important aspect of compact city planning. The temperature decrease caused by replacing the withdrawal area in each compact city model with grassland (Fig. 7) and the temperature increase caused by introducing the corresponding compact city model (Fig. 6) approximately offset each other for the entire time. In short, in compact city planning, it is necessary to properly plan not only for the concentrated urban area but also for treatment of the withdrawal area from the viewpoint of environmental impact, such as mitigation of a more localized heat island phenomenon in the urban area.

5. Conclusions

With the declining population and severe financial situation in recent years in Japan as a background, compact city planning has attracted a lot of attention. Although many local governments in Japan have proposed their own compact city plans, there are no comprehensive plans on prefecture or metropolitan-area scale. Therefore, in this study, we first designed three compact city models with different degrees of compactness for a prefecture in a large metropolitan area of Japan, i.e., for Aichi Prefecture in the Nagoya metropolitan area. The designed models were constructed based on the urban classifications “population-induced area,” “population-unchanged area,” and “withdrawal area.” The design approach on a wider spatial scale is considerably new in Japan.

Next, we introduced the designed compact city models into future (the 2050s) projections of the summer thermal environment by downscaling simulations from a global scale to an urban scale and performed an environmental impact assessment. In addition, the effect of a land use change in the withdrawal area of each compact city model on the future thermal environment in the urban area (the population-induced and population-unchanged areas) was investigated.

Although the environmental impact of introducing the compact city models was less than the impact of the future progress of global warming, a temperature increase in the urban area occurred due to urban densification in the compact city models. The problem became worse as the degree of compactness increased. On the other hand, the problem was basically resolved in the case with a land use change in the withdrawal area (replacement with grassland). The air temperature in the urban area was decreased by the advection effect of lower-temperature air from the grassland. As a result, the temperature decrease in the urban area caused by replacing the withdrawal area with grassland approximately offset the temperature increase caused by introducing the compact city models. This is the most interesting finding of this study and reveals an important aspect of compact city planning. Namely, we need to properly plan not only for the concentrated urban area but also for treatment of the withdrawal area from the viewpoint of environmental impact in compact city planning.

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