Future environmental assessment and urban planning by downscaling simulations

Satoru Iizuka*

Graduate School of Environmental Studies, Nagoya University

* Corresponding author
E-mail address: s.iizuka@nagoya-u.jp
Postal address: Furo-cho, Chikusa-ku, Nagoya, Aichi 464-8603, Japan

Abstract

The outline of a sophisticated downscaling simulation model developed by the author and colleagues and its application for projecting the future urban thermal environment during the progress of global warming are introduced in this paper. Examples of inevitable uncertainties in future projections brought by the choices of a greenhouse gas emissions scenario and general circulation model (GCM) data are also shown. Moreover, three examples of the environmental assessment for future urban planning, i.e., (1) disaster mitigation and prevention urban structure scenario, (2) compact city scenario, and (3) city master plan in a developing country, by the developed downscaling simulation model are presented. Downscaling simulation is a very powerful environmental assessment tool and is very useful for urban planning, especially in the inevitable future global warming period.

Keywords

Future projection, Downscaling simulation, Environmental assessment, Urban planning

1. Introduction

As clearly stated in the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report (2014), “Warming of the climate system is unequivocal.” The increase in the global mean surface air temperature (the globally averaged combined land and ocean surface temperature) for the last 100 years was about 0.6 °C (a warming of 0.85 °C over the period 1880 to 2012 (IPCC, 2014)). The small temperature change, which people cannot clearly recognize, causes various extreme weather events all over the world. Based on the results of various general circulation models (GCMs), it is likely that, in the future, the global mean surface air temperature will continue to rise more rapidly than ever. Under the highest greenhouse gas emissions scenario among the Representative Concentration Pathways (RCPs) (van Vuuren et al., 2011), i.e., RCP8.5, the increase in the surface air temperature by the end of this century (2081-2100) relative to 1986-2005 will likely be in the range of 2.6-4.8 °C (IPCC, 2014).

Currently, more than half of the world’s population lives in urban areas (United Nations, 2018). In urban areas, air temperature increases can be attributed to global warming and urban heat islands. Increases in the annual mean air temperature in the major metropolises of Japan, such as Tokyo, Osaka, and Nagoya, for the last 100 years were about 3 °C (Japan Meteorological Agency, 2017). The temperature increases were mainly due to those cities' urban heat islands. Based on the above-mentioned fact that the temperature increase due to global warming for the last 100 years was about 0.6 °C, the impact of those urban heat islands was about four times greater than that of the past global warming.

However, in the future, the contribution of global warming will be larger than that of the urban heat island in many urban areas in developed countries, especially with population declining. In Japan, the population is declining as birth rates drop and the financial situation worsens. In this social situation, urban areas will not continue to expand as before, and the impact of urban heat islands will decrease. Nevertheless, future urban thermal environments will not improve due to the impact of future global warming. We should adapt the future thermal environments, especially in summers, to a certain degree. Not only mitigation measures but also adaptation measures are required to deal with the severe thermal environments of the future.

In Japan, research projects on climate change adaptation supported by the ministries started approximately 8 years ago. An interdisciplinary (climatology and meteorology, architectural and urban environmental engineering, civil engineering, and computer science) research group has been initiated by the author, and our group has tackled a pioneering research project on climate change adaptation named RECCA (Research Program on Climate Change Adaptation, 2010-2015) supported by the Ministry of Education, Culture, Sports, Science and Technology (MEXT) of Japan. Actually, many social implementations of adaptation (and also mitigation) measures are planned and will be performed on an urban or building scale. Appropriate and quantitative future projections of the thermal environments, especially in summers, on those spatial scales are crucial to considering suitable adaptation and mitigation measures. A downscaling simulation from a global scale to an urban or building scale is a very powerful tool for projecting the microscale thermal environments influenced by future global warming.

In this paper, first, the outline of a sophisticated downscaling simulation model developed by our interdisciplinary research group through the above-mentioned research project (RECCA) is introduced. Our simulation model is a kind of dynamical downscaling technique and consists of GCM data and a model based on Weather Research and Forecasting (WRF) (Skamarock et al., 2008) and large-eddy simulation (LES). The difficulty of merging WRF (a climate simulation model on regional and urban scales) and LES (a microclimate simulation model on a building scale) is also discussed.

Second, future projections of the changes in the urban thermal environment until around the end of this century using the developed downscaling simulation model are shown, and the uncertainties of future projections are discussed. To conduct future projections, various future scenarios (greenhouse gas emissions scenario, land-use and land-cover scenario, urban structure scenario, energy systems scenario, etc.) must be introduced. The choices of future scenarios and GCM data bring uncertainties to future projections.

Third, three examples of the environmental assessment for future urban planning by downscaling simulations are introduced. The final goal of these applications is social implementation. From the perspectives of environmental assessment and disaster mitigation and prevention, future urban structure scenarios for a major metropolitan area in Japan (the Nagoya metropolitan area) are discussed. In the context of future population decline and the global warming period, compact city scenarios for the same metropolitan area with a focus on mitigating the thermal environment are also discussed. Moreover, the environmental assessment of an actual city master plan in a developing country and investigation of some modifications by downscaling simulations are presented.

2. Development of a downscaling simulation model from a global scale to a building scale

2.1. Downscaling techniques

Downscaling techniques have been developed mainly by researchers who specialize in climatology and meteorology. The purposes are to fully grasp the impact of global warming on environments on smaller spatial scales and to consider mitigation and adaptation measures on those spatial scales. Downscaling techniques are broadly divided into two categories: dynamical downscaling (e.g., Wang et al., 2004) and statistical downscaling (e.g., Wilby et al., 2004). The dynamical downscaling technique is a kind of interpolation of GCM data using a regional climate model (RCM). By introducing an RCM, the dynamics and physical processes on regional and urban scales are sufficiently taken into account; however, the computational load becomes large. The statistical downscaling technique is based on statistical relationships between past or present climatic elements on broader scales and those on local scales. The technique is simple to use, and its computational load is small. However, it is difficult to apply the statistical downscaling technique based on past or present climate data to future projections with the progress of global warming.

The downscaling simulation model developed by our interdisciplinary research group and introduced in this paper is based on a dynamical downscaling technique, as shown in Fig. 1. Almost all downscaling simulation models work from a global scale to a regional or urban scale and cannot be applied to a finer spatial scale, i.e., a building scale. In contrast, our model can downscale to a building scale. This is the most significant feature of the model.

The dynamical downscaling technique is divided into two methods: a direct downscaling method and a pseudo global warming method (Kimura and Kitoh, 2007). In the direct downscaling method, GCM data are given to an RCM directly as the initial and boundary conditions. Therefore, the errors and biases of the GCM used are also given to the RCM. Moreover, the processing of all spatial-temporal GCM data is very complicated.

The pseudo global warming method proposed by Kimura and Kitoh (2007) can avoid the problems of the direct downscaling method. In their method, first, the difference between the 10-30-year average of future climatic elements and that of present climatic elements is calculated based on GCM data. Then, the linear coupling of the climatic differences and reanalysis data is given to an RCM as the initial and boundary conditions. The pseudo global warming method is adopted in our downscaling simulation model.

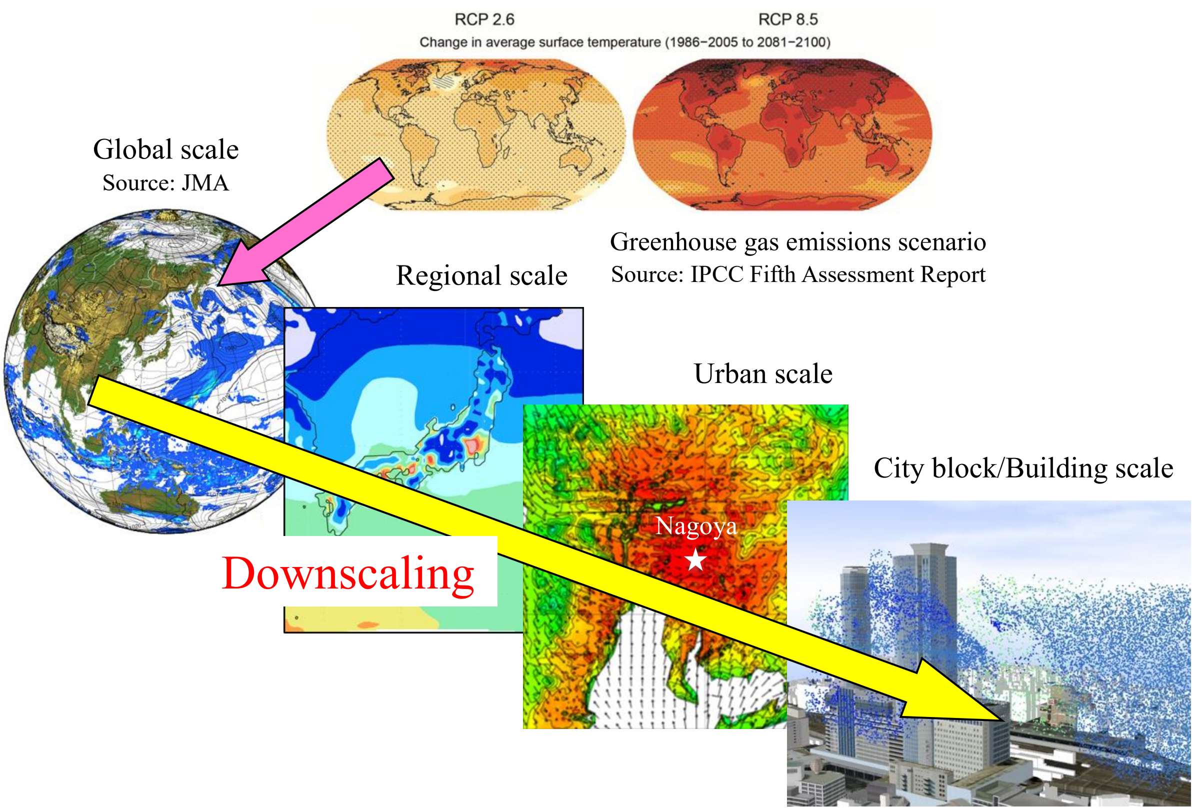


Fig. 1. Outline of our sophisticated downscaling simulation model.

2.2. Difficulty in the development of a downscaling simulation model

As described in Section 2.1, our downscaling simulation model can downscale to a building scale, which is the most significant feature of the model. The downscaling simulation model consists of GCM data and a model based on WRF (Skamarock et al., 2008) and LES. WRF is introduced as the climate simulation model on regional and urban scales, and LES is applied as the microclimate simulation model on a building scale.

One of the biggest difficulties in developing our downscaling simulation model was merging WRF on an urban scale and LES on a building scale. Needless to say, a simulation model on a larger scale cannot capture the fluctuations of climatic elements such as velocity and temperature on a smaller scale. Especially on a building scale, small-scale velocity fluctuations largely affect flow, temperature, and other scalar fields around buildings. Therefore, the boundary conditions of LES, especially the inflow boundary condition, cannot be given by a simple nesting of the WRF results. To successfully downscale to a building scale, appropriate small-scale velocity fluctuations for the inflow boundary condition (inflow turbulence) of LES should be generated separately and incorporated into the WRF results.

Artificial generation methods based on the inverse Fourier transform of prescribed spectra (Lee et al., 1992; Kondo et al., 1997; Iizuka et al., 1999) and the Cholesky decomposition of the Reynolds stresses (Lund et al., 1998; Xie and Castro, 2008) are effective for making appropriate inflow turbulence of LES. No flow simulation is required in those methods; thus, there is little additional computational load. The biggest problem of artificial generation methods is the rapid and unphysical decay of the generated turbulence just behind the inflow boundary. This is because the artificially generated inflow turbulence does not satisfy the governing equations (the continuity and momentum equations), and it changes to satisfy them when it flows downstream.

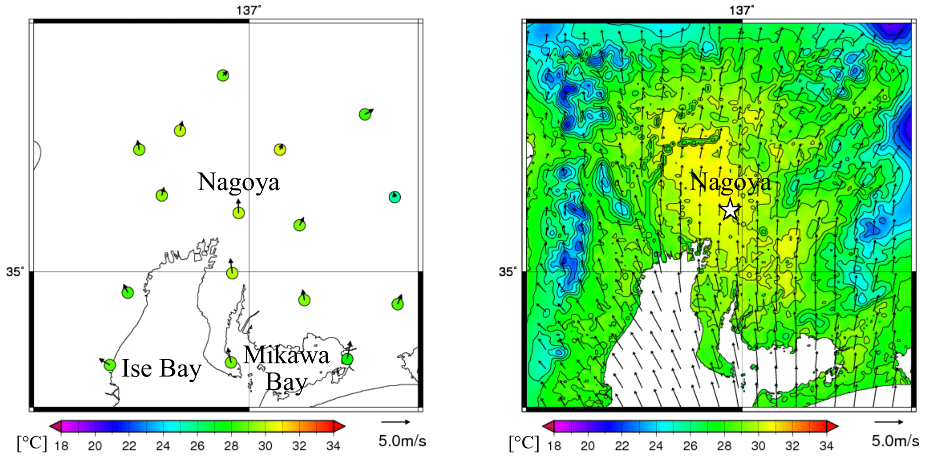
Our downscaling simulation model introduces an artificial method of generating the inflow turbulence of LES based on the Cholesky decomposition of the Reynolds stresses (Xie and Castro, 2008). Inflow turbulence is expressed as the combination of the mean velocity component and its deviation. By obtaining the mean velocity components and the Reynolds stresses from the WRF results, the WRF and LES simulations are merged. The artificial generation method also has a problem that the generated turbulence is rapidly and unphysically attenuated when it flows downstream. We proposed a modified method in which the inflow turbulence generated can satisfy the continuity equation by using Taylor's hypothesis of frozen turbulence and generalized curvilinear coordinate transformation (Xuan and Iizuka, 2014; Iizuka and Xuan, 2016). Unfortunately, the decay of turbulence was not remarkably improved by our modification. In the present stage, for practical applications, inflow turbulence should be generated with consideration of the increment to offset the rapid and unphysical decay of the generated turbulence. Further efforts to solve the common problem of artificial methods of generating the inflow turbulence of LES are required.

2.3. Verification of accuracy

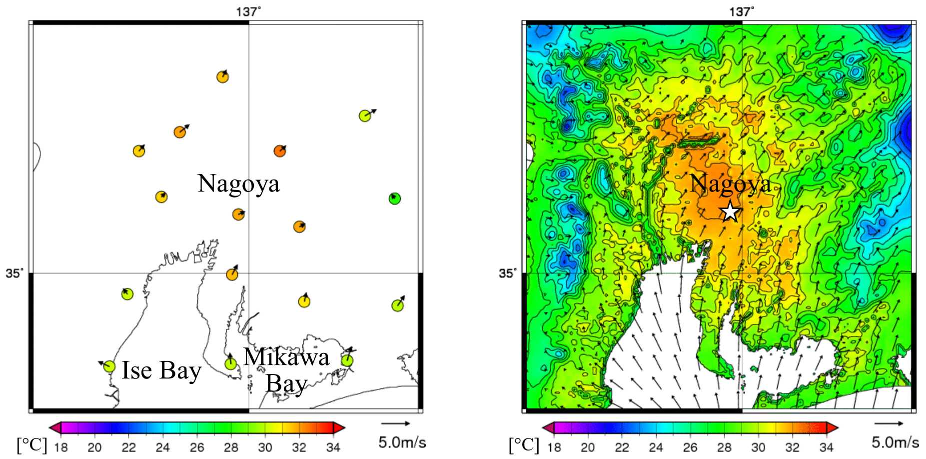
Prior to making future projections that cannot be verified, it is crucial to verify the prediction accuracy of the simulation model to be used, e.g., through a comparison with observational data.

As an example, to verify the performance of our downscaling simulation model, Fig. 2 compares the horizontal distributions of the monthly averaged (for the month of August in each year) air temperature at a height of 2 m and wind velocity vectors at a height of 10 m at 2 p.m. in the Nagoya metropolitan area obtained from the observational data of the Japan Meteorological Agency and the developed downscaling simulation model. The Nagoya metropolitan area, which is located in the central part of Japan, is the third largest metropolitan area in Japan. The simulated results were obtained by downscaling simulations from a global scale via a regional scale to an urban scale.

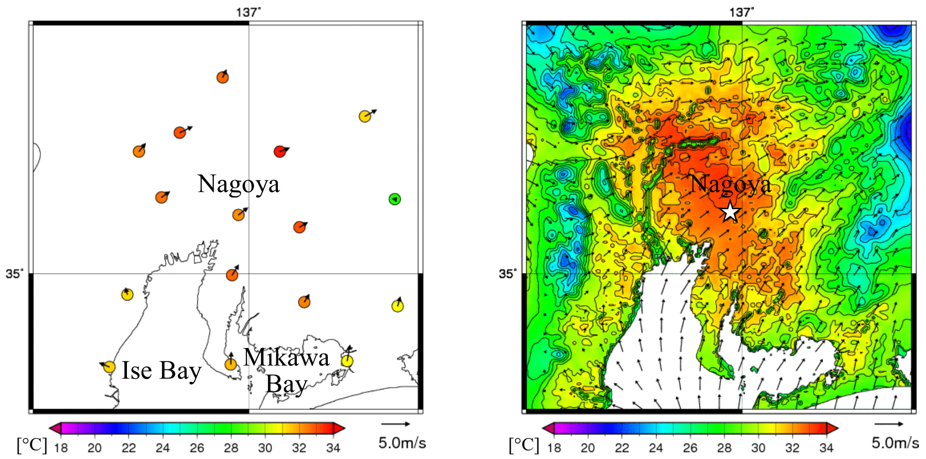
In each year (2014-2016), the simulated results of the temperature and velocity vectors generally correspond well to the observational data. The simulated results also well reproduce the annual variation of the temperature field, such as a cool summer in 2014 and a hot summer in 2016, although the simulated temperatures are a little lower than the observational data.



(1) 2 p.m., August 2014 (Left: Observation; Right: Simulation)



(2) 2 p.m., August 2015 (Left: Observation; Right: Simulation)



(3) 2 p.m., August 2016 (Left: Observation; Right: Simulation)

Fig. 2. Horizontal distributions of the monthly averaged (for the month of August in each year) air temperature at a height of 2 m and wind velocity vectors at a height of 10 m at 2 p.m. in the Nagoya metropolitan area of Japan.

3. Future projections of an urban thermal environment using a downscaling simulation model

3.1. Changes in the urban thermal environment with the future progress of global warming

Projections of future changes in the thermal environment in the Nagoya metropolitan area of Japan (cf. Domain 3 in Fig. 3) from the 2030s to the 2090s based on our downscaling simulation model (cf. Chapter 2) are shown in Fig. 4. Although various future scenarios (greenhouse gas emissions scenario, land-use and land-cover scenario, urban structure scenario, energy systems scenario, etc.) are required to conduct future projections, only the greenhouse gas emissions scenario is introduced in this example application. Some examples of future projections including the future land-use scenario and urban structure scenario are presented in the next chapter. However, it should be noted that the greenhouse gas emissions scenario, which is directly related to the future progress of global warming, is likely the most influential scenario for the change in an urban thermal environment, especially for projections in the more distant future.

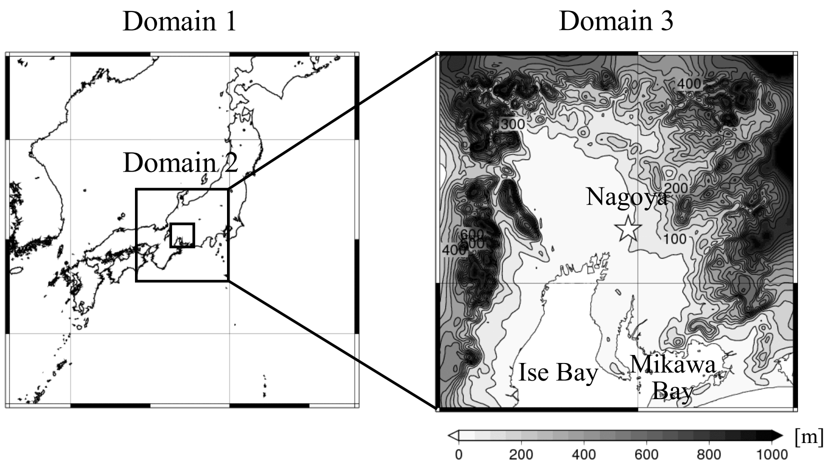
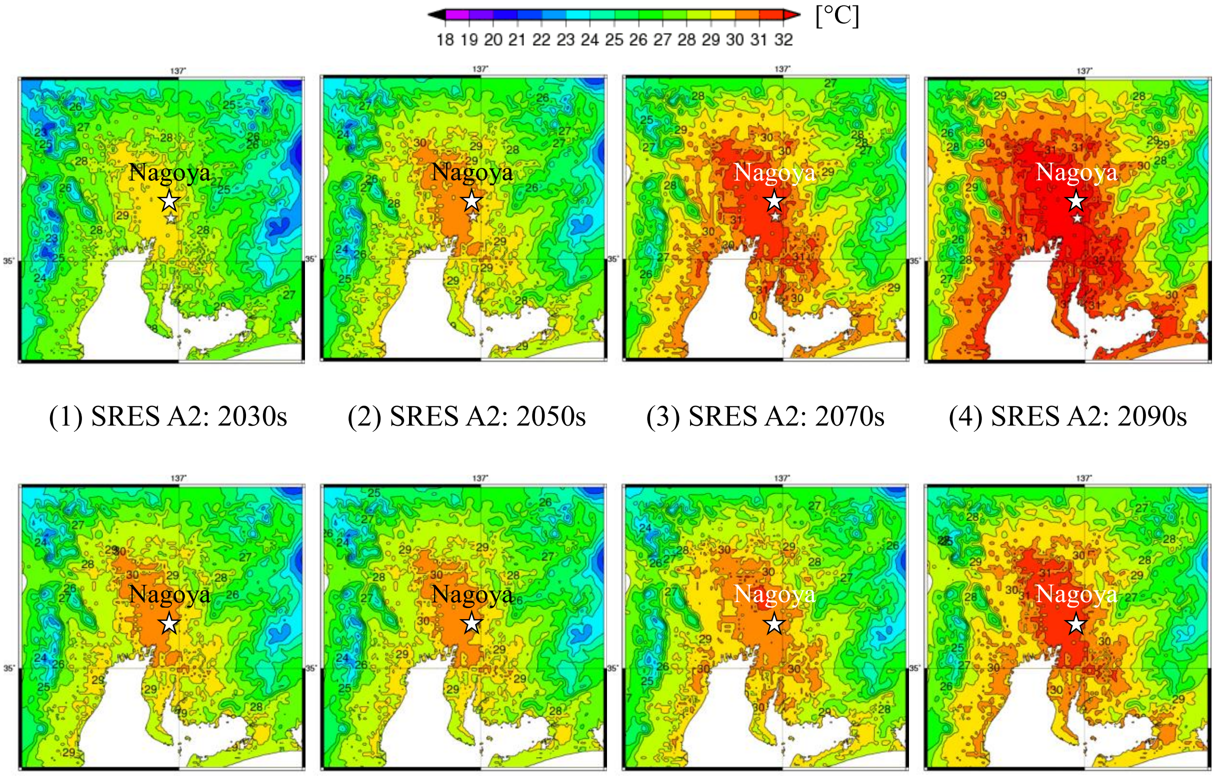


Fig. 3. Three-level nested domains in the WRF projections.

GCM data projected by MIROC 3.2-medres (Nozawa et al., 2007) with the Special Report on Emissions Scenarios (SRES) A2 and B1 (Nakicenovic et al., 2000) (greenhouse gas emissions scenarios) were used for the pseudo global warming method (Kimura and Kitoh, 2007) adopted in our downscaling simulation model (cf. Section 2.1). The underlying themes of SRES A2 and B1 are "regionally oriented economic development" and "economic, social, and environmental sustainability," respectively (IPCC Working Group I, 2007). Future changes of the total radiative forcing in SRES A2 and B1 correspond well to those in RCP8.5 and 4.5, respectively (IPCC Working Group I, 2013). The values of RCPs such as 8.5 (W/m^2) and 4.5 (W/m^2) indicate the approximate total radiative forcing in year 2100 relative to 1750 (IPCC Working Group I, 2013). The positive and larger value of radiative forcing causes more advanced warming of surface temperatures.

Five elements formulating the pseudo global warming data (horizontal winds, potential temperature, geopotential height, sea surface temperature, and ground surface temperature) were used as the initial and boundary conditions in the WRF (Version 3.0.1.1 with the ARW dynamics solver) projections on regional and urban scales. Three-level nesting was adopted in the WRF projections, as shown in Fig. 3. The sizes and horizontal grid resolutions of the nested domains were 1,975 km × 1,975 km × 21 km and 25 km, 500 km × 500 km × 21 km and 5 km, and 120 km × 120 km × 21 km and 1 km. For Domains 1 and 2, the U.S. Geological Survey (USGS) land-use data were applied; on the other hand, the National Land Numerical Information land-use data provided by the Ministry of Land, Infrastructure, Transport and Tourism (MLIT) of Japan were introduced for Domain 3 (the smallest domain). The Noah-LSM was used for the land surface model, and the urban canopy model proposed by Kusaka et al. (2001) was applied in urban areas.

Fig. 4 compares the horizontal distributions of the monthly averaged (for the month of August) air temperature at a height of 2 m in the Nagoya metropolitan area of Japan between the case series of SRES A2 and B1. A remarkable heat island phenomenon in the central part of the metropolitan area can be clearly observed in all cases. As the period advances in both SRES A2 and B1 case series, the heat island becomes hotter due to the corresponding future progress of global warming. However, the projected temperatures in each period are different between SRES A2 and B1. Each temperature difference for the same period between SRES A2 and B1 is a kind of uncertainty in the future projections.



(1) SRES A2: 2030s (2) SRES A2: 2050s (3) SRES A2: 2070s (4) SRES A2: 2090s

(5) SRES B1: 2030s (2) SRES B1: 2050s (3) SRES B1: 2070s (4) SRES B1: 2090s

Fig. 4. Horizontal distributions of the monthly averaged (for the month of August) air temperature at a height of 2 m in the Nagoya metropolitan area of Japan.

3.2. Uncertainties in future projections

Fig. 4 shows an example of uncertainty in future projections caused by the choice of a greenhouse gas emissions scenario. Although the choices or decisions of other future scenarios (land-use and land-cover scenario, urban structure scenario, energy systems scenario, etc.) also produce uncertainties, the biggest impact on the change in an urban thermal environment is likely brought by a greenhouse gas emissions scenario. This reflects the seriousness of projected future global warming.

In addition to the choices or decisions of various future scenarios, the choices of simulation models cause large uncertainties in future projections. In particular, the choice of a GCM (GCM data) significantly affects the projected results. Fig. 5 compares increases in the monthly averaged (for the month of August) air temperature at a height of 2 m in and around Japan for 2040-2069 relative to 1970-1999 among a total of 33 GCMs. Large differences among the GCM results can be observed under both RCP4.5 and 8.5. The maximum temperature differences under RCP4.5 and 8.5 are approximately 2.4 °C (GFDL-CM3 – INMCM4). The difference exceeds the model ensemble-averaged temperature increase under RCP4.5 (about 1.8 °C) and is nearly equal to that under RCP8.5 (about 2.5 °C). This demonstrates a large uncertainty in the future projections.

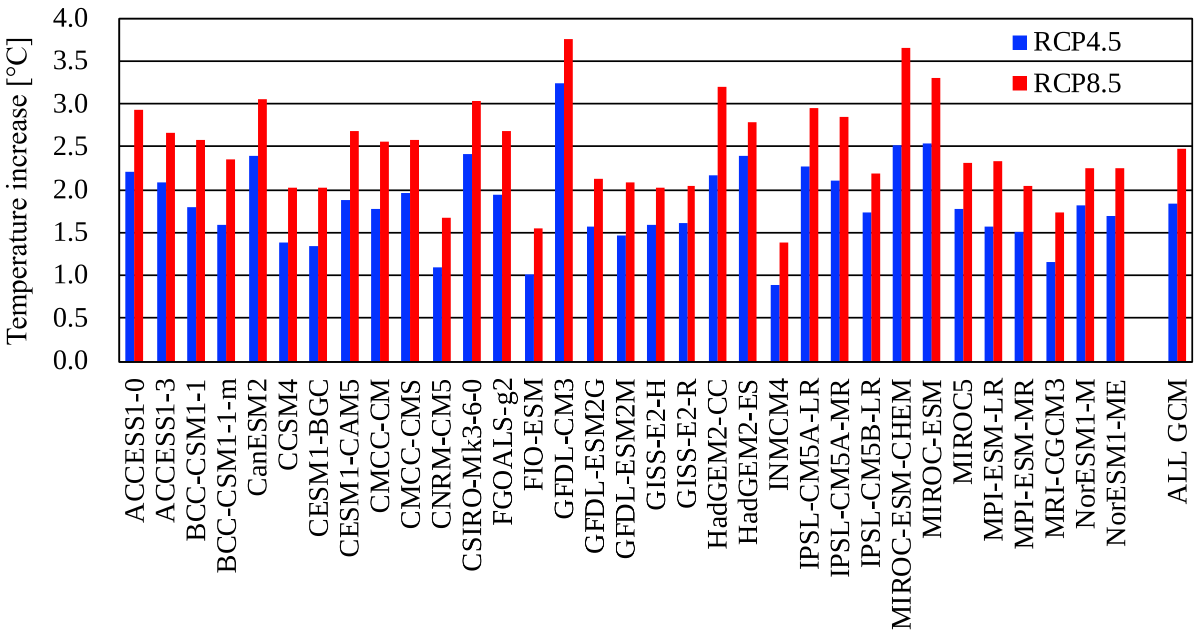


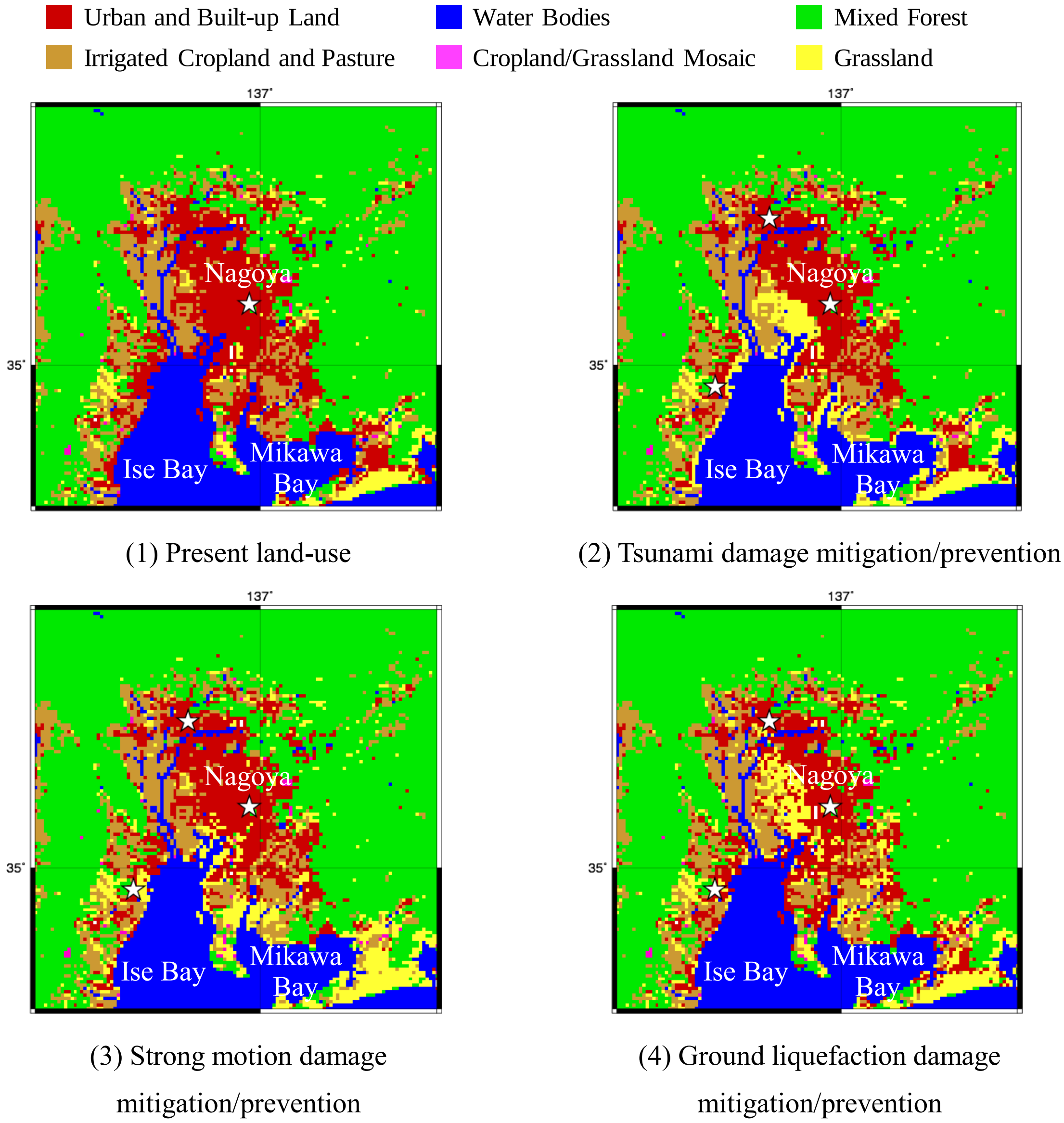
Fig. 5. Comparison of increases in the monthly averaged (for the month of August) air temperature at a height of 2 m in and around Japan for 2040-2069 relative to 1970-1999 among a total of 33 GCMs.

Future projections, which cannot be verified, include various inevitable uncertainties. Therefore, adequate investigation and understanding of the sensitivities of future scenarios and those of simulation models are crucial. Moreover, multi-scenario ensemble analysis and multi-model ensemble analysis are highly recommended to quantitatively evaluate the ranges of their uncertainties.

4. Environmental assessment for future urban planning by downscaling simulations

4.1. Impact of disaster mitigation and prevention urban structure scenarios

In a wide region including the Nagoya metropolitan area, the third largest metropolitan area in Japan, a huge earthquake and the following disasters (tsunami and ground liquefaction) are expected in the near future. From the perspective of disaster mitigation and prevention, we designed three future urban structure scenarios, shown in Fig. 6 (Iizuka et al., 2015a). A 20% reduction of the urban area from the present land-use, which is the same reduction ratio as the projected population decline for the 2050s, is assumed in each scenario. The area heavily damaged by each disaster in the case of a huge earthquake's occurrence (Cabinet Office, Government of Japan, 2012 and 2013) corresponds to the future reduction of the urban area, and the area is changed to grassland.



(1) Present land-use

(2) Tsunami damage mitigation/prevention

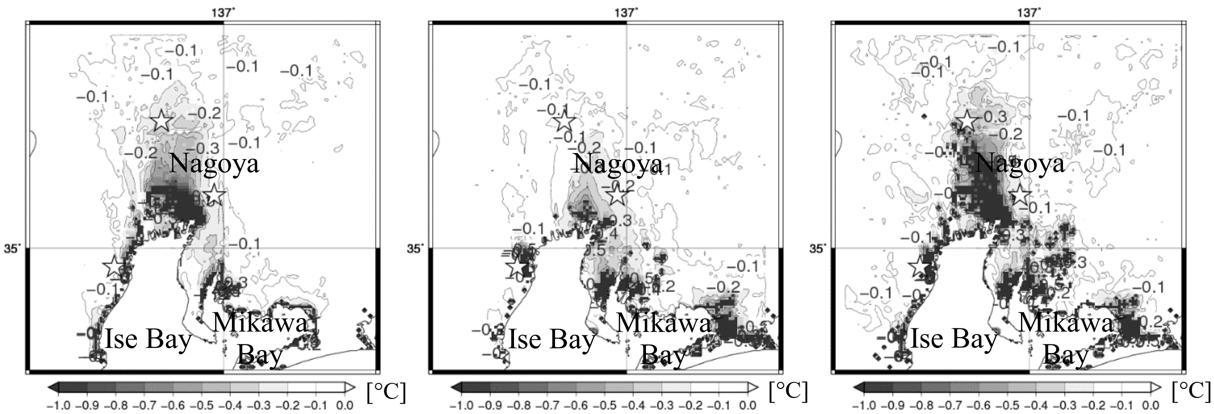
(3) Strong motion damage mitigation/prevention

(4) Ground liquefaction damage mitigation/prevention

Fig. 6. Land-use distributions of disaster mitigation/prevention urban structure scenarios for the Nagoya metropolitan area of Japan (Iizuka et al., 2015a).

Future projections of the urban thermal environment in the summer (August) of the 2050s were performed by introducing the disaster mitigation/prevention urban structure scenarios (Iizuka et al., 2015a). A downscaling simulation method like that used in Chapter 3 was adopted for the future projections. GCM data projected by MIROC 3.2-medres (Nozawa et al., 2007) with SRES A2 (Nakicenovic et al., 2000) were used for the pseudo global warming method (Kimura and Kitoh, 2007).

Fig. 7 is an example of the projected results and shows the horizontal distributions of the difference in the monthly averaged (for the month of August in the 2050s) air temperature at a height of 2 m at 6 p.m. between each disaster mitigation/prevention urban structure scenario and the present land-use scenario (Iizuka et al., 2015a). Sea breezes from Ise Bay and Mikawa Bay blow remarkably at that time (6 p.m.). The area heavily damaged by each disaster is mainly near the shore and is changed to grassland (cf. Fig. 6). According to the change, the sea breezes reach areas farther downstream, and, as a result, the air temperature in the corresponding areas of each disaster mitigation/prevention urban structure scenario decreases as compared with that under the present land-use scenario. The effective introduction of sea breezes contributes to the mitigation of the severe urban thermal environment. The proposed urban structure scenarios are meaningful not only from a disaster mitigation/prevention perspective but also from the perspective of improving the thermal environment.



(1) Tsunami damage mitigation/prevention

(2) Strong motion damage mitigation/prevention

(3) Ground liquefaction damage mitigation/prevention

Fig. 7. Horizontal distributions of the difference in the monthly averaged (for the month of August in the 2050s) air temperature at a height of 2 m at 6 p.m. between each disaster mitigation/prevention urban structure scenario and the present land-use scenario (Iizuka et al., 2015a).

4.2. Impact of compact city scenarios

Recently in Japan, the concept of a compact city is gathering a great deal of attention due to the projected population decline. In collaboration with researchers who specialize in urban planning, we designed three compact city scenarios for the Nagoya metropolitan area of Japan based on the present situation evaluations of disaster mitigation/prevention, public transportation, public facilities, and living facilities. The concentration level is different in each compact city scenario, as shown in Fig. 8. Withdrawal areas increase as the concentration level becomes higher.

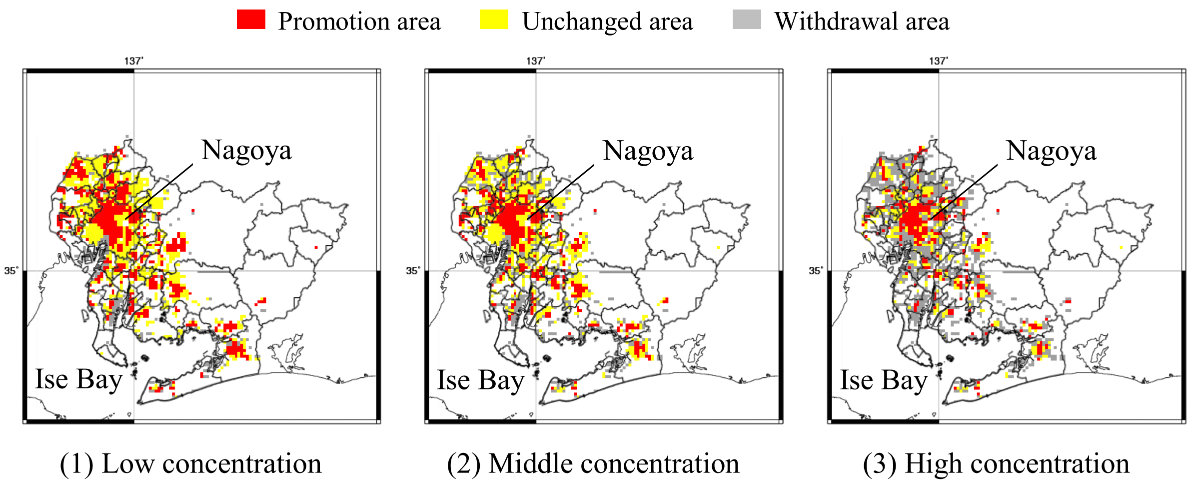


Fig. 8. Compact city scenarios for the Nagoya metropolitan area of Japan.

Future projections of the urban thermal environment in the summer (August) of the 2050s were performed by introducing the compact city scenarios. A downscaling simulation method like that used in Section 4.1 was adopted for the future projections, although GCM data and the greenhouse gas emissions scenario, whose choices cause large uncertainties in future projections (cf. Section 3.2), were changed to GFDL-CM3 (Donner et al., 2011) data and RCP8.5 (van Vuuren et al., 2011), respectively, in this example application.

An interesting result is shown in Fig. 9. The space-averaged (over the whole urban area) and monthly averaged (for the month of August in the 2050s) diurnal variations of the difference in air temperature at a height of 2 m between the cases with and without rearranging the withdrawal areas are compared in Fig. 9, and those between each compact city scenario and the present land-use scenario are compared in Fig. 10. With regard to Fig. 9, the withdrawal areas are replaced by grassland in cases with rearrangement; on the other hand, buildings in the withdrawal areas remain as vacant buildings in cases without rearrangement. Actually, in Japan, the number of vacant buildings (and also vacant spaces) is increasing rapidly, and it has become a social problem due to safety and sanitary reasons.

As shown in Fig. 9, the temperature averaged over the whole urban area decreases with the rearrangement of the withdrawal areas. The temperature decrease in each compact city scenario roughly offsets the temperature increase due to the urban concentration in the corresponding scenario shown in Fig. 10. This suggests that the rapid rearrangement of withdrawal areas is required in compact city planning.

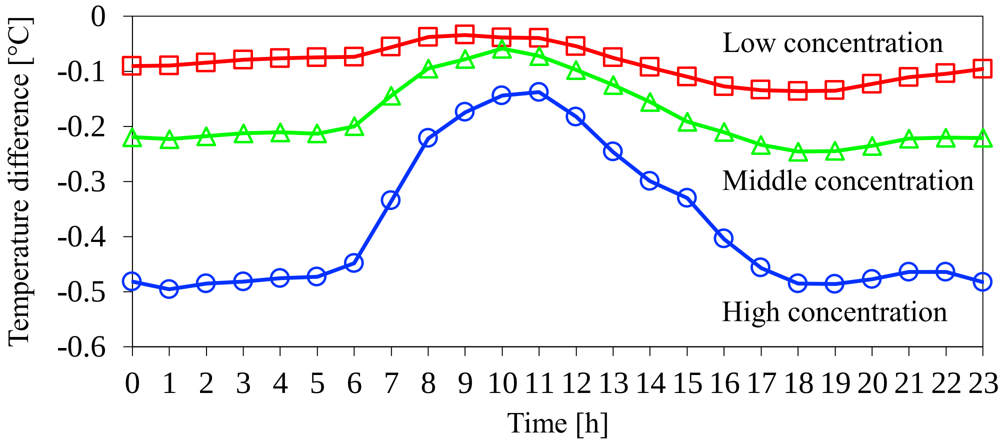


Fig. 9. Space-averaged (over the whole urban area) and monthly averaged (for the month of August in the 2050s) diurnal variations of the difference in air temperature at a height of 2 m between the cases with and without rearranging the withdrawal areas in the compact city scenarios.

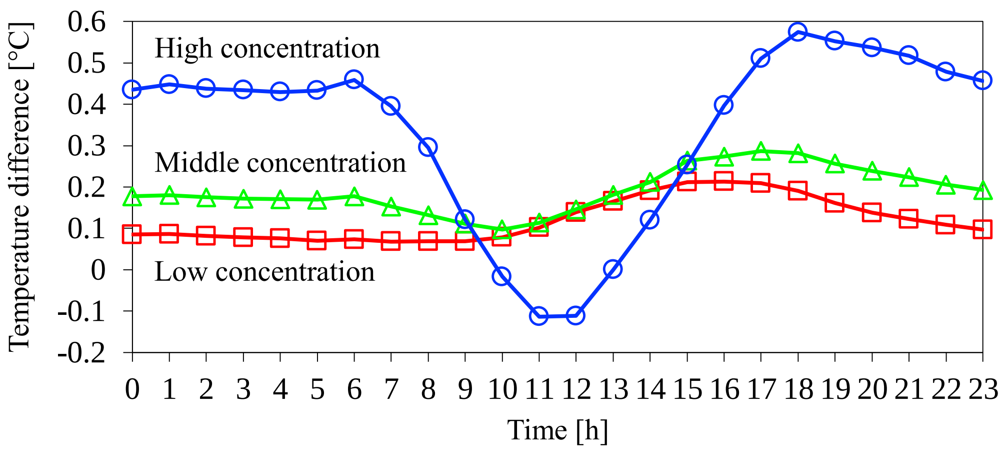
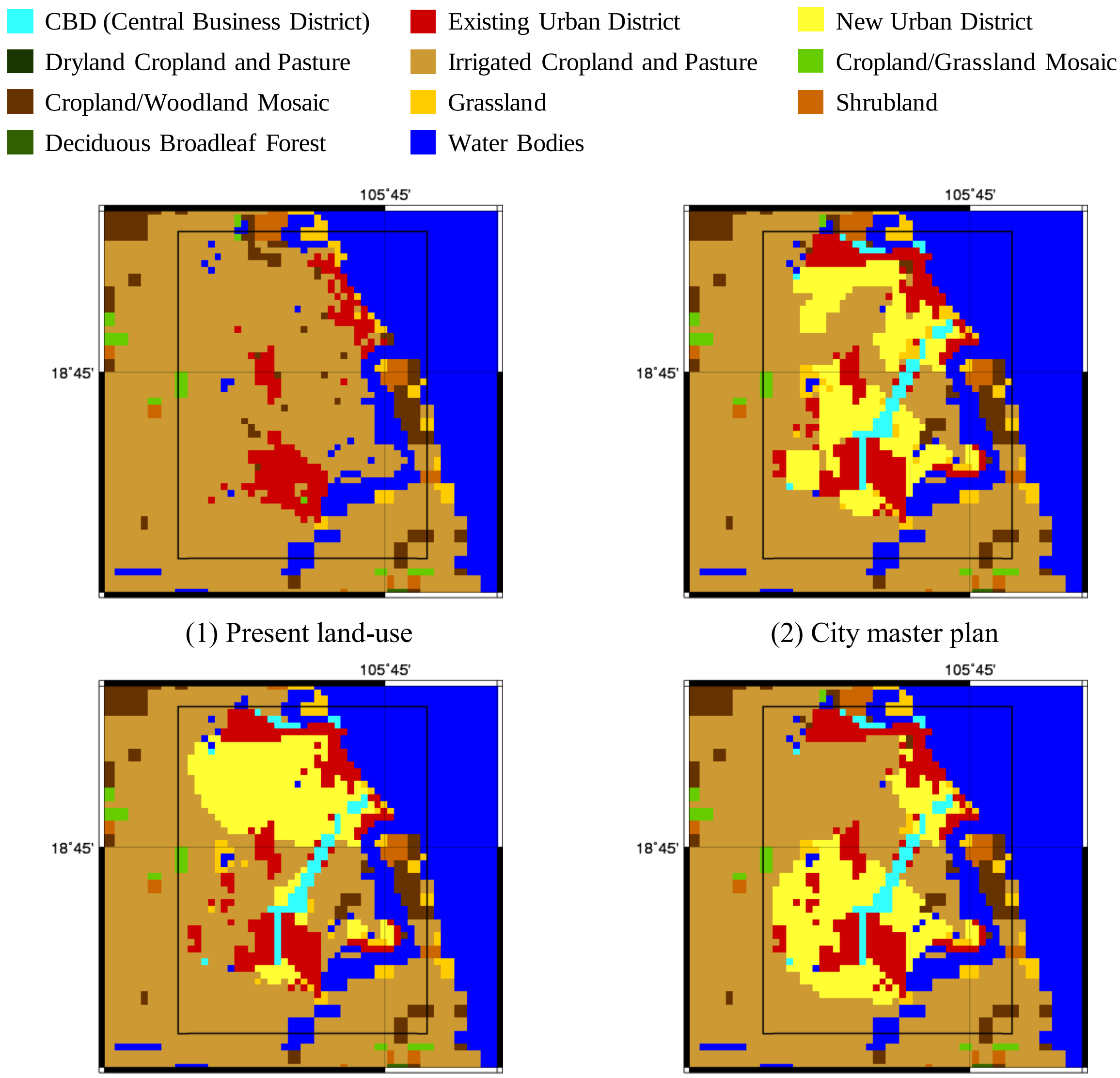


Fig. 10. Space-averaged (over the whole urban area) and monthly averaged (for the month of August in the 2050s) diurnal variations of the difference in air temperature at a height of 2 m between each compact city scenario and the present land-use scenario.

4.3. Impact of a city master plan in a developing country

Finally, an attempt to project the urban thermal environment in the summer (June) of the 2030s in Vinh City, Vietnam, after implementing a city master plan and its modifications is introduced (Iizuka et al., 2015b). The plan was proposed by a Japanese civil engineering consulting company, Nikken Sekkei Civil Engineering Ltd., and targets the year 2030 with a population of 900,000. The total planning area covers approximately 250 km^2. Fig. 11 shows the land-use distributions of the city master plan and its modifications. By using our downscaling simulation model, future projections of the urban thermal environment after implementing the city master plan and its modified plans were performed. The downscaling simulation method was the same as that adopted in Section 4.2, in which GCM data projected by GFDL-CM3 (Donner et al., 2011) with RCP8.5 (van Vuuren et al., 2011) were used for the



(1) Present land-use

(2) City master plan

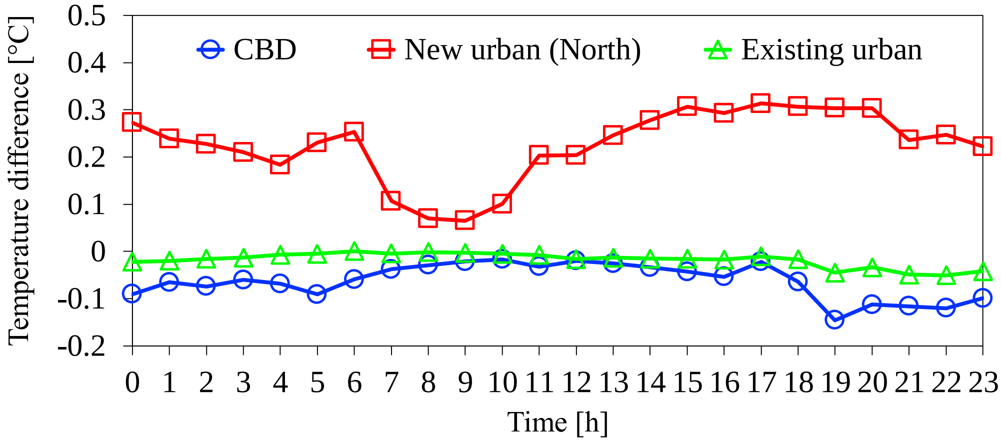
(3) Modified master plan: Northern concentration of the new urban districts

(4) Modified master plan: Southern concentration of the new urban districts

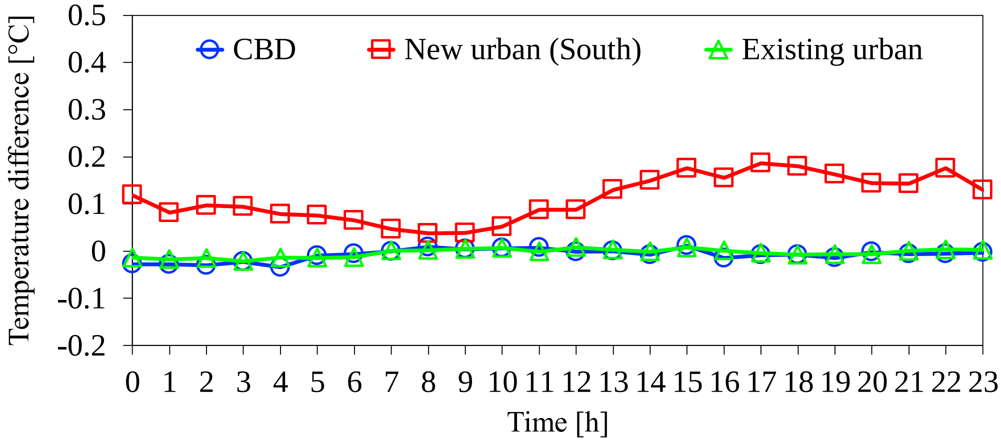
Fig. 11. Land-use distributions of a city master plan for Vinh City in Vietnam and its modifications (Iizuka et al., 2015b).

pseudo global warming method (Kimura and Kitoh, 2007).

As an example of the projected results, Fig. 12 shows the space-averaged (over each urban category) and monthly averaged (for the month of June in the 2030s) diurnal variations of the difference in air temperature at a height of 2 m between each modified plan and the original city master plan (Iizuka et al., 2015b). The temperatures averaged over the whole new urban district in both modified plans are higher than that in the original city master plan. From the perspective of the thermal environment, the original city master plan, in which new urban districts are decentralized in both the northern and southern parts of the planning area, is better than the two modified plans (northern or southern concentration of the new urban districts).



(1) Modified master plan: Northern concentration of the new urban districts



(2) Modified master plan: Southern concentration of the new urban districts

Fig. 12. Space-averaged (over each urban category) and monthly averaged (for the month of June in the 2030s) diurnal variations of the difference in air temperature at a height of 2 m between each modified plan and the original city master plan (Iizuka et al., 2015b).

5. Conclusions

As some examples of applications are shown in this paper, downscaling simulation is a very powerful environmental assessment tool and is very useful for urban planning, especially in the inevitable future global warming period. In actual urban planning, many aspects, such as social infrastructure, disaster mitigation/prevention, nature and historic building conservation, and economic circumstances, should be thoroughly considered. The aspect of mitigating and adapting the thermal environment is also crucial for urban planning in the inevitable future global warming period. Especially in future urban planning for cities in developing countries located in tropical areas, mitigation and adaptation measures to severe thermal environments due to the inevitable global warming and advanced urban heat islands will be very important planning elements.

In future projections using a downscaling simulation model, various inevitable uncertainties are included, and it is desirable to carefully investigate the uncertainties and evaluate them quantitatively.

Multi-scenario ensemble analysis and multi-model ensemble analysis are very useful for evaluating the ranges of uncertainties quantitatively, although the computational loads increase significantly.

Acknowledgments

The author would like to express his sincere gratitude to Dr. Y. Xuan (Tokyo Polytechnic University) for her significant contributions to all of the research presented in this paper. The author is also grateful to the members of our interdisciplinary research group through RECCA (Prof. H. Kusaka (University of Tsukuba), Dr. H. Kondo (National Institute of Advanced Industrial Science and Technology), Prof. M. Kanda (Tokyo Institute of Technology), Dr. M. Hara (Center for Environmental Science in Saitama), Dr. S. Adachi (Riken), Dr. T. Ihara (University of Tokyo), Dr. A. Inagaki (Tokyo Institute of Technology), Dr. M. Nakayoshi (Tokyo University of Science), Dr. Y. Takane (National Institute of Advanced Industrial Science and Technology), and the others) for their great contributions to the development of the sophisticated downscaling simulation model introduced in this paper. Moreover, the author would like to thank Dr. T. Kubota (Hiroshima University), Dr. C. Takatori (Nagoya University), Dr. M. Miyata (Mitsubishi UFJ Research and Consulting), and Ms. K. Watanabe (Nikken Sekkei Civil Engineering) for their valuable comments and advice on city master plans.

References

Cabinet Office, Government of Japan, 2012. http://www.bousai.go.jp/jishin/nankai/model/. (in Japanese)

Cabinet Office, Government of Japan, 2013. http://www.bousai.go.jp/jishin/nankai/taisaku_wg/pdf/20130528_honbun.pdf. (in Japanese)

Donner, L. J., Wyman, B. L., Hemler, R. S., Horowitz, L. W., Ming, Y., Zhao, M., Golaz, J. C., Ginoux, P., Lin, S. J., Schwarzkopf, M. D., Austin, J., Alaka, G., Cooke, W. F., Delworth, T. L., Freidenreich, S. M., Gordon, C. T., Griffies, S. M., Held, I. M., Hurlin, W. J., Klein, S. A., Knutson, T. R., Langenhorst, A. R., Lee, H. C., Lin, Y., Magi, B. I., Malyshev, S. L., Milly, P. C. D., Naik, V., Nath, M. J., Pincus, R., Ploshay, J. J., Ramaswamy, V., Seman, C. J., Shevliakova, E., Sirutis, J. J., Stern, W. F., Stouffer, R. J., Wilson, R. J., Winton, M., Wittenberg, A. T., Zeng, F., 2011. The dynamical core, physical parameterizations, and basic simulation characteristics of the atmospheric component of the GFDL global coupled model CM3. Journal of Climate, 24, 3484-3519.

Iizuka, S., Murakami, S., Tsuchiya, N., Mochida, A., 1999. LES of flow past 2D cylinder with imposed inflow turbulence. Proceedings of the 10th International Conference on Wind Engineering, 1291-1298.

Iizuka, S., Xuan, Y., Kondo, Y., 2015a. Impacts of disaster mitigation/prevention urban structure models on future urban thermal environment. Sustainable Cities and Society, 19, 414-420.

Iizuka, S., Ito, T., Miyata, M., 2015b. Impacts of a future city master plan on thermal and wind environments in Vinh city, Vietnam. Proceedings of the 9th International Conference on Urban Climate, 4pp.

Iizuka, S., Xuan, Y., 2016. Development of a seamless merging method of mesoscale/regional meteorological models and engineering LES models (Part 2): A proposal of imposing the continuity condition on artificially generated inflow turbulence for LES and its application for the analysis of a plane boundary layer flow. Transactions of AIJ, Journal of Environmental Engineering, 81(727), 811-819. (in Japanese)

Intergovernmental Panel on Climate Change Working Group I, 2007. Climate Change 2007: The Physical Science Basis.

Intergovernmental Panel on Climate Change Working Group I, 2013. Climate Change 2013: The Physical Science Basis.

Intergovernmental Panel on Climate Change, 2014. Climate Change 2014: Synthesis Report.

Japan Meteorological Agency, 2017. http://www.data.jma.go.jp/cpdinfo/himr/h29/himr_2016.pdf, 63pp. (in Japanese)

Kimura, F., Kitoh, A., 2007. Downscaling by pseudo global warming method. The Final Report of the ICCAP, 43-46.

Kondo, K., Murakami, S., Mochida, A., 1997. Generation of velocity fluctuations for inflow boundary condition of LES. Journal of Wind Engineering and Industrial Aerodynamics, 67-68, 51-64.

Kusaka, H., Kondo, H., Kikegawa, Y., Kimura, F., 2001. A simple single-layer urban canopy model for atmospheric models: Comparison with multi-layer and slab models. Boundary-Layer Meteorology, 101, 329-358.

Lee, S., Lele, S. K., Moin, P., 1992. Simulation of spatially evolving turbulence and the applicability of Taylor's hypothesis in compressible flow. Physics of Fluids, A4(7), 1521-1530.

Lund, T. S., Wu X., Squires, K. D., 1998. Generation of turbulent inflow data for spatially-developing boundary layer simulations. Journal of Computational Physics, 140(2), 233-258.

Nakicenovic, N., Alcamo, J., Davis, G., de Vries, B., Fenhann, J., Gaffin, S., Gregory, K., Grübler, A., Jung, T. Y., Kram, T., La Rovere, E. L., Michaelis, L., Mori, S., Morita, T., Pepper, W., Pitcher, H., Price, L., Riahi, K., Roehrl, A., Rogner, H. H., Sankovski, A., Schlesinger, M., Shukla, P., Smith, S., Swart, R., van Rooijen, S., Victor, N., Dadi, Z., 2000. Special Report on Emissions Scenarios (SRES). Cambridge University Press, Cambridge.

Nozawa, T., Nagashima, T., Ogura, T., Yokohata, T., Okada, N., Shiogama, H., 2007. Climate change simulations with a coupled ocean-atmosphere GCM called the Model for Interdisciplinary Research on Climate: MIROC. CGER's Supercomputer Monograph Report, 12.

Skamarock, W. C., Klemp, J. B., Dudhia, J., Gill, D. O., Barker, D. M., Duda, M. G., Huang, X. Y., Wang, W., Powers, J. G., 2008. A description of the Advanced Research WRF version 3. NCAR/TN-475+STR, NCAR Technical Note.

United Nations, 2018. World Urbanization Prospects: The 2018 Revision.

Van Vuuren, D. P., Edmonds, J., Kainuma, M., Riahi, K., Thomson, A., Hibbard, K., Hurtt, G. C., Kram, T., Krey, V., Lamarque, J. F., Masui, T., Meinshausen, M., Nakicenovic, N., Smith, S. J., Rose, S. K., 2011. The representative concentration pathways: An overview. Climatic Change, 109, 5-31.

Wang, Y., Leung, L. R., McGregor, J. L., Lee, D. K., Wang, W. C., Ding, Y., Kimura, F., 2004. Regional climate modeling: Progress, challenges, and prospects. Journal of the Meteorological Society of Japan, 82(6), 1599-1628.

Wilby, R. L., Charles, S. P., Zorita, E., Timbal, B., Whetton, P., Mearns, L. O., 2004. Guidelines for use of climate scenarios developed from statistical downscaling methods. Supporting material of the Intergovernmental Panel on Climate Change, 27pp.

Xie, Z. T., Castro, I. P., 2008. Efficient generation of inflow conditions for large eddy simulation of street-scale flows. Flow, Turbulence and Combustion, 81(3), 449-470.

Xuan, Y., Iizuka, S., 2014. Effects of imposing the continuity condition on artificially generated inflow turbulence for LES. Proceedings of the 6th International Symposium on Computational Wind Engineering, 8pp.