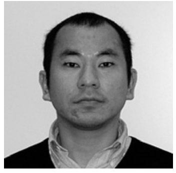
Y. Kawamoto

Effect of urbanization on the urban climate in coastal city, Fukuoka-Kitakyushu metropolitan area, Japan

Yoichi Kawamoto[1]

[1] *Kyushu University, 4-9-1 Shiobaru, Minamiku, Fukuoka, Japan, kawamoto@design.kyushu-u.ac.jp*

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1. Introduction

Currently, 53.6% of the world's population is living in urban areas and that figure is predicted to continue increasing (United Nations, Department of Economic and Social Affairs Population Division, Population Estimates and Projections Section, 2014). However, many cities are facing problems caused by urbanization. The urban heat island phenomenon, one of the urban climate problems, is a typical environmental problem encountered in dense urban areas during summer. The use of sea breeze to mitigate the urban heat island phenomenon has attracted attention in coastal cities. Statistics show that approximately 40% of the world's population lives within 100 km of the coast (World Resources Institute, 2001). Further investigation of the environment in urban areas near the coast is, therefore, important.

Japan is a mountainous island nation, and therefore, most of the large cities in Japan are located in coastal areas. In this study, Fukuoka-Kitakyushu metropolitan area was targeted for investigation. Fukuoka-Kitakyushu metropolitan area is the fourth largest metropolitan area after Tokyo, Osaka, and Nagoya, all of which are coastal cities. Within these areas, sea breezes are important factors mitigating the air temperature rise during summer. However, ongoing urbanization could be changing not only the mechanism of the energy balance on urban surface, but also the sea breeze system in large coastal cities.

Fukuoka-Kitakyushu metropolitan area is comprised of the cities of Fukuoka and Kitakyushu in Fukuoka prefecture located in Kyushu region. The heat island monitoring report (Japan Meteorological Agency, 2015) said that rise of annual average air temperature in last one century in Fukuoka, the central part of Fukuoka-Kitakyushu metropolitan area, is the second largest at 3.1 °C after that in Tokyo at 3.2 °C. Moreover, the rise of minimum air temperature during summer in the last one century in Fukuoka has been reported to be the largest at 3.9 °C.

To clarify the effects of urbanization in the Fukuoka-Kitakyushu metropolitan area, a meso-scale meteorological model named the Weather Research and Forecasting model (WRF) developed by the National Center for Atmospheric Research (Skamorock et.al., 2008) was adopted for analysis. In the WRF model, land-use data provided by the U.S. Geological Survey (USGS) is utilized by default. To represent the urbanization process in the study area, the National Land Numerical Information land-use data (hereafter referred to as NLNI land-use data) provided by the National Land Information Division, National Spatial Planning and Regional Policy Bureau, Ministry of Land, Infrastructure, Transport and Tourism (MILT) of Japan were used to represent the progress of urbanization. USGS global land-use data were derived from 1-km Advanced Very High Resolution Radiometer spans during a 12-month period from April 1992 to March 1993. NLNI land-use data were recorded only in Japan but were published in several years from 1976 to 2009. This data is mesh data with a resolution of approximately 1 km, and each mesh has fractional land-use categories. This feature is very helpful in investigating the urbanization process for several decades. In this study, NLNI land-use data for 1976 (earliest) and 2009 (latest) were utilized to investigate the effect of urbanization in Fukuoka-Kitakyushu metropolitan area.

2. Methods

2.1 Analysis model

The WRF ver. 3.6.1 was used to analyse atmospheric conditions of the Fukuoka-Kitakyushu metropolitan area. From the WRF ver. 3.6, mosaic land-use categories option for the Noah Land Surface Model (LSM) was incorporated. In the previous LSM, land surface property of each analysis mesh was defined by dominant land-use category. If one analysis mesh consisted of 60% ‘Urban’ land-use and 40% ‘Forest’ land-use, that mesh was defined as Urban, and the characteristics of Forest were neglected. In addition, the mosaic LSM enables the representation of different land-use fractions in each analysis mesh. Land use conversion to ‘urban’ in an already urbanized area within a short time period shows little difference. Therefore, mosaic LSM is useful in analysing urban climate transition caused by urbanization for several decades, which is not represented in the dominant land-use category.

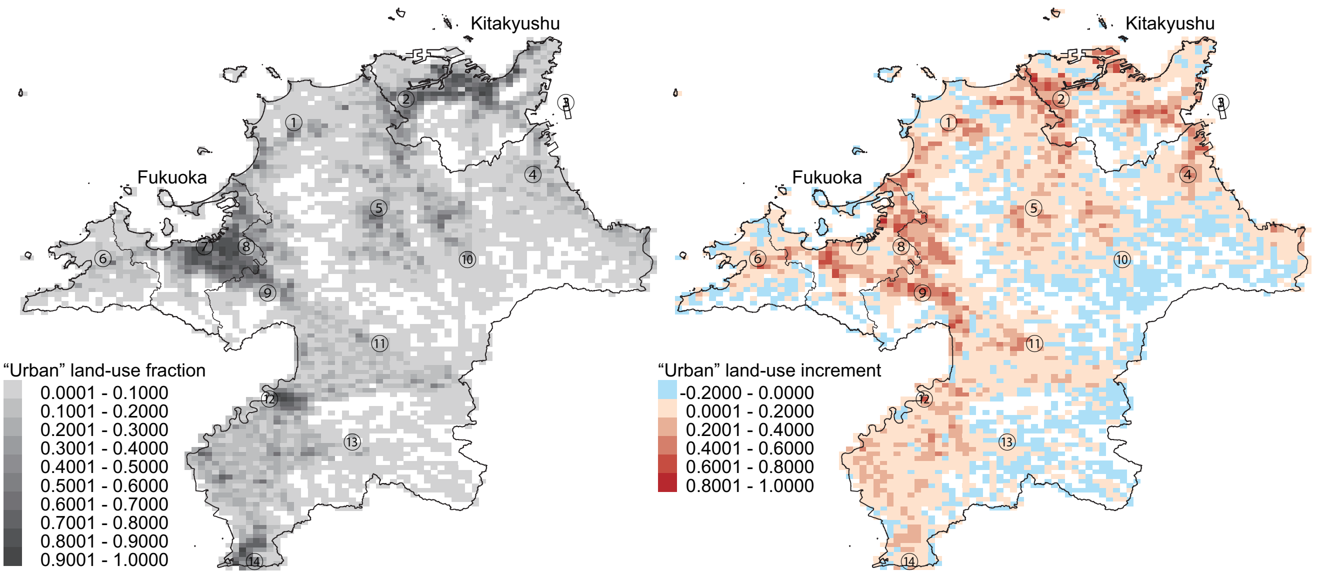
2.2 Outline of National Land Numerical Information land-use data

In this study, the NLNI land-use data were used to represent the progress of urbanization. The data were published in 1976, 1987, 1991, 1997, 2006, and 2009. From these, two datasets that were published in 1976 (earliest) and 2009 (latest) were used. The NLNI land-use data are stored on the basis of the ‘Basic Grid Square’ (Third Area Partition) with a resolution of approximately 1 km^2 and a grid spacing with latitude and longitude of 30" and 45", respectively. The Basic Grid Square is widely used in statistics regarding population, land-use, and urban planning, among others, by national and local governments in Japan. A resolution of approximately 1 km^2 is suitable as input data to the meso-scale model. Each Basic Grid Square has fractional land-use data with different categories according to years. Since each dataset comprises different land-use categories, original land-use categories were re-categorized into six categories of land-use to adapt to the WRF as shown in Table 1.

Figure 1 a) shows the fraction of land under the Urban category (shaded in Table 1) in Fukuoka prefecture in 1976. The resolution of the figure is 1 km and the dark tone indicates the fraction of Urban land-use within a 1 km^2 mesh. Figure 1 b) shows the increment in the Urban land-use fraction over time. Urban land-use fractions in 1976 were subtracted from those in 2009, and therefore, a positive value (red colour in Fig. 1 b) indicates urbanization in that mesh. Overall, the results obtained for the three selected decades did not show extremely rapid urbanization in the Fukuoka-Kitakyushu metropolitan area. In particular, the increments in Urban land-use in the central part of Fukuoka city were very small because this area had already been extensively urbanized by the 1970s. However, Urban land-use area had increased in the surrounding areas because urban sprawl had progressed.

Table 1. Land-use categories in the Weather Research and Forecasting model and National Land Numerical Information land-use dataset.

Land-use categories in WRF	NLNI land-use data (1976)	NLNI land-use data (2009)
Irrigated Cropland and Pasture	Paddy field	Paddy field
Mixed Dryland /Irrigated Cropland and Pasture	Field	Other agricultural land
	Orchard	
	Other tree plantation	
Mixed Forest	Forest	Forest
Barren or Sparsely Vegetated	Wasteland	Wasteland
		Golf course
Urban and Built-Up Land	Land for Building	Land for building
	Trunk transportation land	Trunk transportation land (Road)
		Trunk transportation land (Rail)
	Other land	Other land-use
Water Bodies	Lake	River basin, lake, and marsh
	River	
	Beach	Beach
	Seawater body	Seawater body



a) ‘Urban’ land-use fraction in 1976 *b) Increment in ‘Urban’ land-use from 1976 to 2009*

Fig. 1. ‘Urban’ land-use fraction in Kyushu Prefecture: a) ‘Urban’ land-use fraction in 1976. The dark tone indicates the fraction of ‘Urban’ land-use within each mesh. b) Increase in the ‘Urban’ land-use fraction. The red tone indicates increase in the ‘Urban’ land-use fraction from 1976 to 2009 and the blue tone indicates decrease.

2.3 Analysis conditions

Figure 2 illustrates the analysis domains, which covered an area of 3,000 km (east-west) × 2,500 km (south-north) with a horizontal resolution of 25 km. The entire analysis domain was two-way nested into two-fold sub-domains: domain 2 (750 × 750 km with a resolution of 5 km) and domain 3 (200 × 180 km with a resolution of 1 km). The vertical domain was divided into 40 unequally spaced grids. The top was set by pressure at 5,000 Pa, and the lowest grid height was approximately 60 m.

The summer of 2013 was selected as the study period. During that period, the average air temperature in the western part of Japan was the highest among observations by Japan Meteorological Agency since 1946. The simulations were started on 1 June, and time integration was performed for 92 days. Results of hourly output data for 62 days from July and August are discussed in this paper. The initial conditions were obtained from the NCEP FNL Operational Global Analysis data. Relaxation lateral boundary conditions were applied to domain 1 and nest lateral boundary conditions were applied to domains 2 and 3. Surface temperature and sea surface temperature for setting lower boundary conditions were obtained from the NCEP FNL data. In this study, the following schemes were applied for all domains and all cases. Microphysics: Thompson scheme (Thompson et. al., 2004); Long-wave radiation: RRTM scheme (Mlawer et. al., 1997); Short-wave radiation: Goddard scheme (Chou and Suarez, 1994); Surface layer: Eta similarity scheme based on Monin–Obukhov similarity (Janjic, 2002); Land surface: Noah LSM model (Chen and Dudhia, 2001) with mosaic option; Planetary boundary layer: Mellor–Yamada–Janjic scheme (Janjic. 2002). Grell 3D ensemble cumulus parameterization was applied only for domain 1. Urban canopy models were not applied for all domains because of lack of detailed building parameters. Therefore, the effect of urbanization was represented by urban land-use, and transition of urban morphology could not be considered.

In this study, to evaluate the climatological effect of the urbanization process over the three decades, numerical simulations were performed using two different land-use datasets. For simplicity, these two datasets are abbreviated as 'case 76' for land-use dataset for 1976, and 'case 09' for 2009. In order to evaluate the influence of urbanization, the same meteorological datasets were adopted as the initial conditions for both cases.

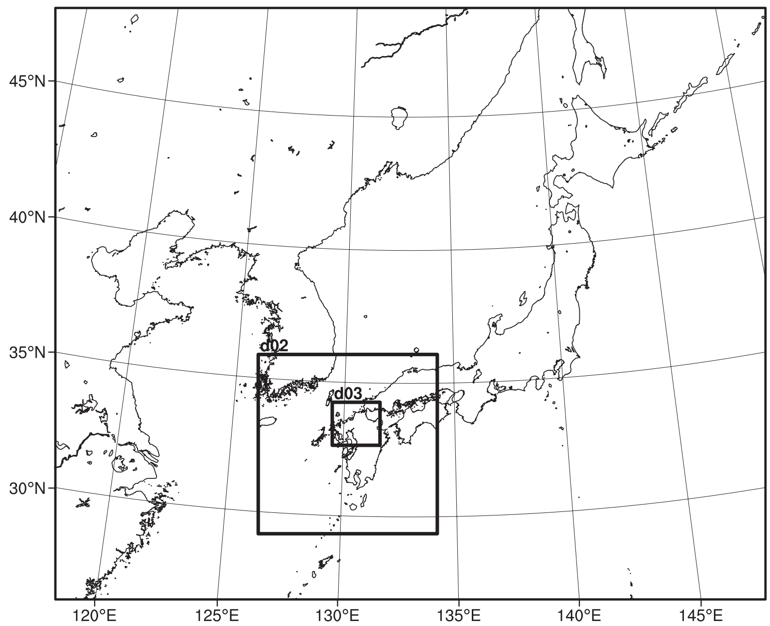


Fig. 2. Analysis domains for the Weather Research and Forecasting model simulation. Domain 1 covers entire Japan, domain 2 covers the entire Kyushu region, and domain 3 covers the northern part of Kyushu region, which was the main target area in this study.

3. Results

3.1 Comparing observation and simulation results

Case 09 utilized latest land-use data and the year was close to the simulation period in 2013; therefore, to validate the simulation performance, results of case 09 were first compared with the observation data provided by Japan Meteorological Agency (JMA). In Fukuoka prefecture, surface air temperatures at 14 sites are being observed. Locations of observation sites are shown in Fig. 1. Table 2 shows the Mean Error (ME) and Root Square Mean Error (RMSE) for observed surface air temperature and simulated air temperature at 2 m above ground level. Data for averaging were hourly data for 62 days of July and August. The domain used for this evaluation was domain 3, with a resolution of 1 km.

ME became negative at 12 sites; simulation underestimated surface air temperature. RMSE showed a range from 1.55 to 2.72. These results suggested that significant errors had occurred. One possible reason for these errors is the representativeness of the results. With the mosaic option, LSM has the capability to represent land-use fraction in each analysis mesh. On the other hand, to avoid the effect of surrounding terrestrial objects, the circumference of JMA observation sites over 30 m^2 are grass. The simulation tends to represent land-use fraction, and observation tends to avoid land-use fraction. This unconformity may cause these errors. Further investigation of simulation errors is still needed.

Table 2. Mean error (ME) and root mean square error (RMSE) for surface air temperature when comparing JMA observation and simulation results for case 09.

Site	ME	RMSE
1. Munakata	-0.73	2.66
2. Yahata	-0.41	1.79
3. Kuko-kitamachi	-1.84	2.72
4. Yukuhashi	-0.38	1.95
5. Iizuka	-0.10	1.75
6. Maebaru	-1.38	2.21
7. Fukuoka	-0.77	2.18
8. Hakata	0.07	1.84
9. Dazaifu	-0.50	1.80
10. Soeda	-0.43	1.81
11. Asakura	-0.23	1.72
12. Kurume	-0.56	1.72
13. Kurogi	-0.32	1.67
14. Omuta	0.41	1.55

3.2 Frequency of sultry nights

In summer in Japan, sultry nights cause damage to human health. Specifically, a sultry night is defined as a day in which the minimum air temperature during the night exceeds 25 °C. In this study, a sultry night is treated as a day in which the minimum air temperature exceeds 25 °C without considering the time of occurrence. Table 3 shows the frequency of sultry nights in July and August for cases 76 and 09, and the observation results. Only for case 09, predictive values are also shown. Here, predictive value means rates for days on which both simulation and observation results showed a sultry night or both simulation and observation results did not show a sultry night.

Predictive values for case 09 showed a range from 60 to 85 %, and the average was 75 %. Compared with cases 76 and 09, the frequency of sultry nights was higher in 11 sites. This result suggested that urbanization in the targeted area worsens the urban environment at night.

Table 3. Frequency of sultry nights for simulation cases 76 and 09 and JMA observation results.

Site	Case 76	Case 09		Observation
	Frequency	Frequency	Predictive value	Frequency
1. Munakata	19	20	60%	29
2. Yahata	27	34	63%	43
3. Kuko-kitamachi	40	39	69%	46
4. Yukuhashi	15	24	69%	33
5. Iizuka	24	28	61%	31
6. Maebaru	23	33	68%	41
7. Fukuoka	49	50	85%	49
8. Hakata	39	49	77%	44
9. Dazaifu	20	39	71%	40
10. Soeda	16	15	73%	9
11. Asakura	16	21	73%	17
12. Kurume	19	32	68%	42
13. Kurogi	10	7	74%	13
14. Omuta	35	39	74%	26

3.3 Surface air temperature

Fig. 3 shows the difference in air temperature at 2 m above ground level between case 76 and case 09. Hourly data of air temperature for 62 days of July and August were averaged only on the land surface. Averaged air temperatures of case 76 were subtracted from that of case 09, so negative values (blue tone in Fig. 3) indicate that the air temperature in case 76 was higher than that in case 09, and positive values (red tone in Fig. 3) indicate that the air temperature in case 76 was higher than that in case 09.

As mentioned above, central parts of Fukuoka and Kitakyushu (darker colour in Fig. 1 a) were already urbanized in the 1970s, so air temperature rise caused by urbanization in this area was small. On the other hand, because of urban sprawl, urban heat island phenomenon had expanded. Although some parts in Fig. 3 show air temperature drop, air temperature difference averaged over the land surface of domain 3 shows +0.11 °C.

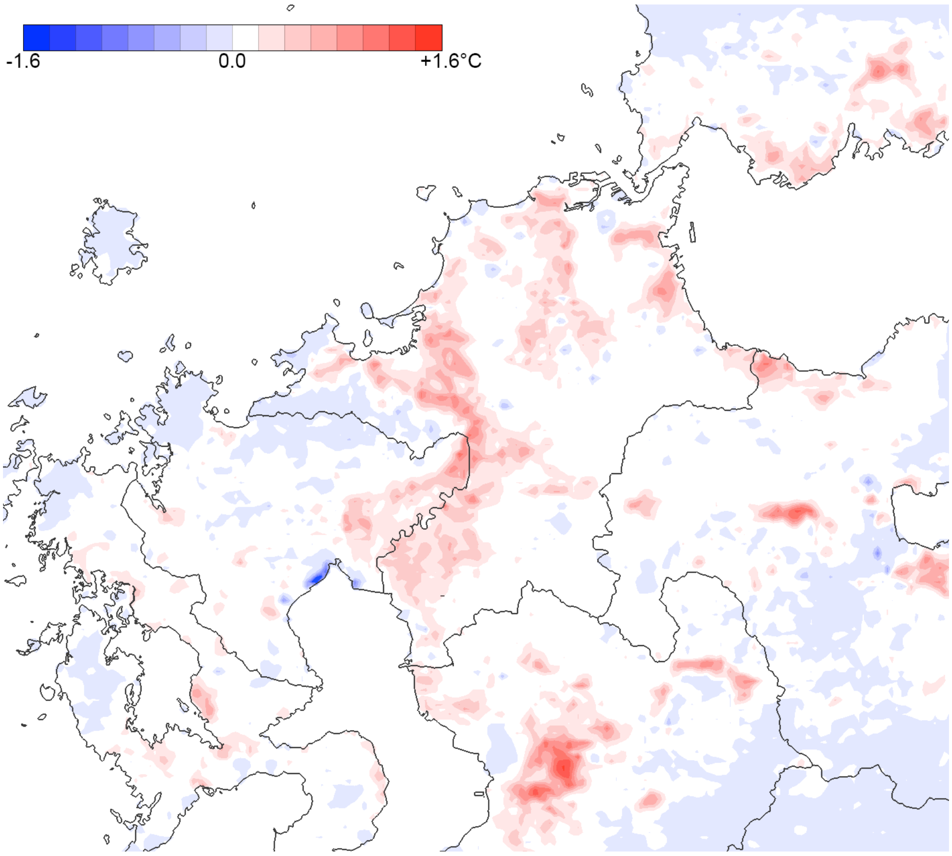


Fig. 3. Difference of averaged air temperature between case 76 and case 09 over July and August. Blue tone shows temperature drop and red tone shows temperature rise from case 76 to case 09. Spatial average of this domain is +0.11 °C.

4. Summary

In this study, the National Land Numerical Information (NLNI) land-use fractions data for Japan were used to represent the progress of urbanization in Fukuoka-Kitakyushu metropolitan area using a land surface model with mosaic option in WRF. NLNI land-use data were published for several years, and the earliest data set published in 1976 and latest one published in 2009 were adopted to represent the urbanization in about three decades. The investigation period was set in summer of 2013; record heat was observed in this year in western part of Japan. To clarify the effect of urbanization, same meteorological and simulation conditions are applied to two simulation cases except for land-use fraction data. Urban canopy models were not applied because of lack of detailed building parameters in 1976. Therefore, the effect of urbanization is represented by urban land-use.

The results showed that urban sprawl in Fukuoka-Kitakyushu metropolitan area caused the expansion of urban heat island and increased the frequency of sultry nights. In this study, the urbanization process was represented by land-use change alone. Since urbanization also involves changes in the intensity of anthropogenic heat release, urban morphology, the surface properties of buildings, and so on, further investigation into the effects of urbanization on the urban climate is, therefore, still required.

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