Article

Relationship between city size, coastal land use and summer daytime air temperature rise with distance from coast

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Abstract: The relationship between city size, coastal land use and air temperature rise with distance from coast during summer day is analyzed using the meso-scale Weather Research & Forecasting (WRF) model in five coastal cities in Japan with different sizes and coastal land use (Tokyo, Osaka, Nagoya, Hiroshima and Sendai) and inland cities in Germany (Berlin, Essen and Karlsruhe). Air temperature increased as distance from the coast increased, reached its maximum, and then decreased slightly. In Nagoya and Sendai, the number of urban land use in coastal areas is less than the other three cities, where air temperature is a little lower. As a result, air temperature difference between coastal and inland urban area is small and the curve of air temperature rise is smaller than those in Tokyo and Osaka. In Sendai, air temperature in the inland urban area is the same as in the other cities, but air temperature in the coastal urban area is a little lower than the other cities, due to about one degree lower sea surface temperature influenced by the latitude. In three German cities, the urban boundary layer may not develop sufficiently because the fetch distance is not enough.

Keywords: distance from coast; air temperature; land use; city size; Japan; Germany

1. Introduction

Urban heat island intensity is defined by the air temperature difference between an urban area and its surrounding suburbs. Oke [1] revealed that urban heat island intensity is proportional to the logarithm of the population, based on observations in a number of cities in North America and Europe. Fukuoka [2] and Park [3] both showed the same relationship in Japanese and Korean cities and revealed that the slope of the relationship is steep for cities with more than 300,000 people. Sakakibara and Kitahara [4] also showed a similar relationship for cities in Nagano Prefecture, Japan; however, the change in slope, such as that found by Fukuoka [2] and Park [3], was not obtained.

In these studies, population was used to indicate the degree of urbanization. An increase in population, for example, was associated with high-rise buildings and land use change, as well as with an expansion of the urban area. More specific indicators, such as urban area, artificial land coverage, and average building height, should be used to implement more effective heat island countermeasures. The mesoscale Weather Research & Forecasting (WRF) model (Skamarock et al. [5]), which is used generically worldwide, is effective for these studies (Iizuka et al. [6], Kusaka et al. [7]). Moriyama et al. [8] have reported that air temperature is more influenced by the building

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coverage rate than the building height. When the building coverage rate is small or the building height is low, air temperature is low.

In this study, for the purpose of actual recognition of urban heat island phenomenon, as the target five coastal cities in Japan with different sizes and coastal land use (Tokyo, Osaka, Nagoya, Hiroshima, Sendai), we have analyzed the relationship between city size, coastal land use and air temperature rise with distance from coast during summer day, while the other factors such as the climatic environment depending on the surrounding topography, the shape of the coastline, the location would be considered. In the previous study, the authors confirmed that air temperature near ground surface observed in the daytime during the summer days in Osaka City was explained by the distance from the coast, rather than building volume ratio, artificial exhaust heat, natural coverage ratio, roughness length (Takebayashi et al. [9]). Kusaka et al. [10] have simulated numerically the effects of land-use alternation on the sea breeze and daytime heat island in the Tokyo metropolitan area. By comparison between 1900 and 1985, they pointed out the more clearly definition of the sea breeze front, two hours delay of the sea breeze arrival to the inland area and the maximum temperature rise in the inland area. Yamaoto et al. [11] have investigated the relationship between sea breeze penetration and anomalously high summer daytime temperatures in the inland suburbs of Tokyo, with consideration of the relative position of sea breeze fronts, by using data from the high-density temperature observation network (Extended-METROS). The high temperature in the inland area was considered based on the penetration condition of the sea breeze. The original definition of urban heat island intensity by Oke [1] is the annual maximum air temperature difference. However, since the higher air temperature in the summer is noticed socially, which causes the deterioration of the thermal environment in outdoor space and the increase of energy consumption, the higher air temperature period of summer was selected as the objective period in this study. It was targeted at 14:00, when the maximum temperature is likely to occur. Hardin et al. [12] have analyzed regional air temperature variability and urban heat island magnitude by using a high-density network of urban and rural weather stations. They pointed out the need for consideration of spatial distribution of air temperature for the analysis of urban heat island intensity. The spatial distribution of air temperature was treated as the object in this study. In addition, we have analyzed similarly for inland cities (Berlin, Essen and Karlsruhe in Germany).

2. Outline of Calculation

We used mesoscale Weather Research & Forecasting (WRF) model (version 3.0.1.1-ARW). For the turbulence model (planetary boundary layer scheme), we used the Mellor-Yamada-Janjic model. The Noah-LSM was used for the land surface model, and the urban canopy model was applied in urban areas (Kusaka et al. [13]). The objective study areas are shown in Figures 1 and 2. The outer square is domain 1 (3 km grid, 360 km square) and the inner filled square is domain 2 (1 km grid, 103 km square). The nesting technique was used in each region. The calculation results of air temperature at 2 m high and wind velocity at 10 m high in domain 2 were used for the analysis.

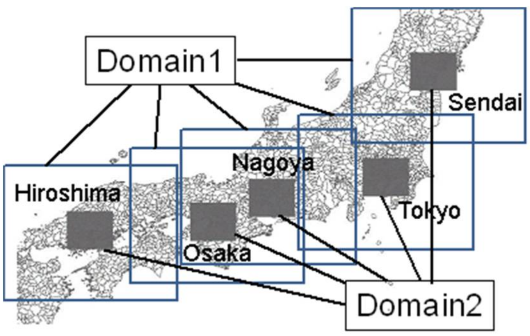

Figure 1. Objective study areas in Tokyo, Osaka, Nagoya, Hiroshima, Sendai (Domain 1: 3 km grid, 360 km square, Domain 2: 1 km grid, 103 km square).

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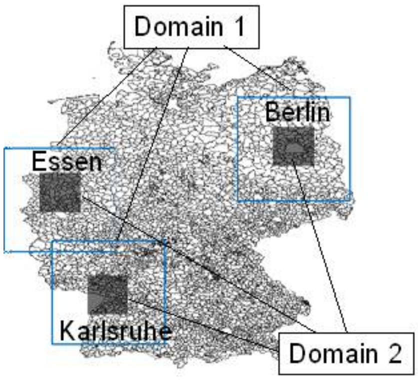

Figure 2. Objective study areas in Berlin, Essen, Karlsruhe (Domain 1: 3 km grid, 360 km square, Domain 2: 1 km grid, 103 km square).

Calculation conditions are shown in Table 1. The period for which calculations were done was from August 1 to 31, 2010 for Japanese cities, from July 23 to August 23, 2008 for German cities. In Japanese cities, based on digital national land information (spatial resolution of 100 m) and a normalized vegetation index (NVI) created from Landsat7 ETM+ data, urban areas were classified into three categories according to the previous study (Kitao et al. [14]): high-rise and high-density, middle-rise and moderate-density, and low-rise and low-density. In German cities, they were classified based on USGS data as shown in Table 1.

Table 1. Calculation conditions for WRF model.

		for Japanese cities	for German cities
Period		August 1 - 31, 2010	July 23 - August 23, 2008
Vertical grid		28 layers (surface - 100 hPa)	
Horizontal grid		Domain 1: 3 km (120 x 120 grids) Domain 2: 1 km (103 x 103 grids)	
Meteorological data		JMA: Meso-scale analysis (3 hourly, 10 km grid, 20 layer)	
		NECP: final analysis (6 hourly, 1 degree grid, 17 layer)	
Geographical data	Terrain height	Digital map (50m x 50m resolution)	United States Geological Survey (about 100m x 100m resolution)
	Land use	Digital national land information (about 100m x 100m resolution) + NVI	
Microphysics process		Purdue Lin et al. scheme	
Radiation process	Long wave	RRTM long wave scheme	
	Short wave	Dudhia short wave scheme	
Planetary boundary layer process		Mellor-Yamada-Janjic PBL scheme	
Surface process	Urban area	UCM (Urban Canopy Model)	
	Non urban area	Noah LSM	
Cumulus parameterization		None	
Four-dimensional data assimilation		None	

Land use conditions and number of urban meshes in Tokyo, Osaka, Nagoya, Hiroshima, Sendai and Berlin, Essen, Karlsruhe are shown in Figures 3 and 4. The numbers of urban land use meshes are 3,698 in Tokyo, 1,271 in Osaka, 1,416 in Nagoya, 364 in Hiroshima, 239 in Sendai, 460 in Berlin, 637 in Essen and 38 in Karlsruhe. Frequency of urban land use at each distance point from the coast for Japanese cities is shown in Figure 5. Main wind direction is not specified for German cities where the natural land use is located around the city. Frequency of urban land use in Japanese cities is larger in the coastal area and decreased gradually in the inland area. The number of urban land use meshes along the coastal area in Nagoya and Sendai is slightly smaller compared to those for Tokyo, Osaka and Hiroshima.

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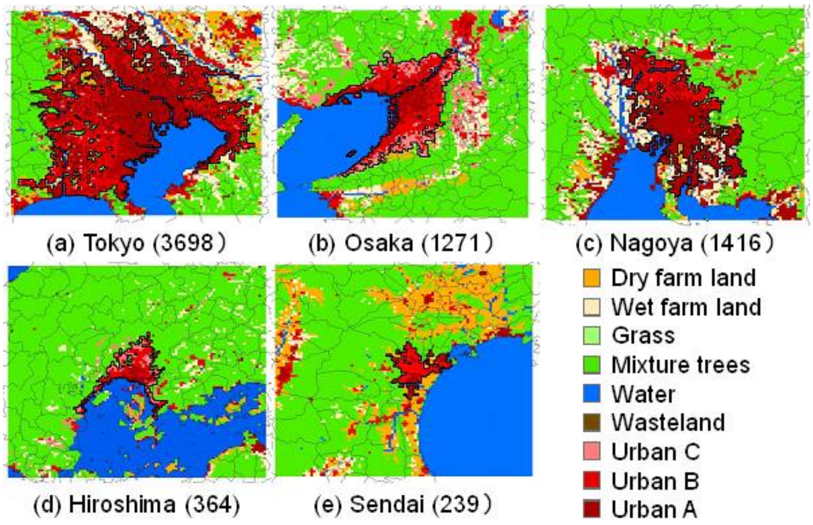

Figure 3. Land use conditions and number of urban meshes in Tokyo, Osaka, Nagoya, Hiroshima, Sendai (1 km grid, 103 km square).

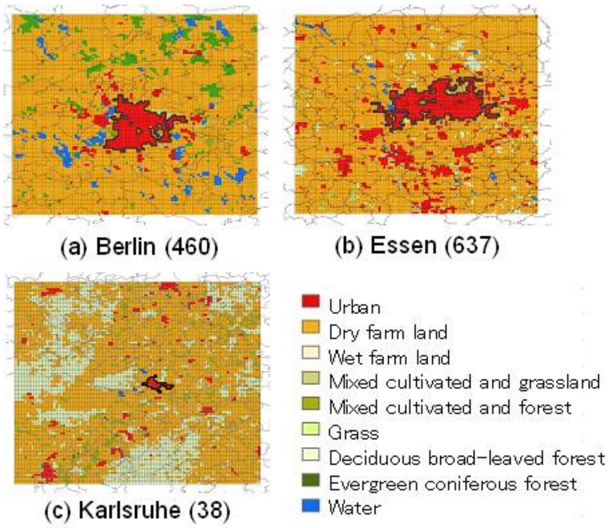

Figure 4. Land use conditions and number of urban meshes in Berlin, Essen, Karlsruhe (1 km grid, 103 km square).

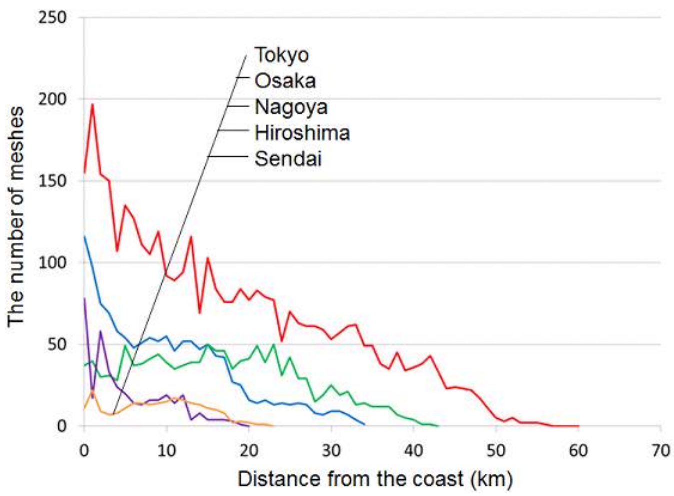

Figure 5. Frequency of urban land use at each distance point from the coast.

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3. Calculation Accuracy

Fine days conditions were selected according to weather conditions as follows; weather: mostly sunny and sunny, sunlight hours: more than 7.0 hours, solar radiation: more than 19 MJ/m^2, precipitation: less than 0.5 mm. Sea breeze conditions only for Japanese cities were selected according to weather conditions as follows; wind velocity: more than 2.0 m/s at observatory, wind direction: main wind direction at each observatory, duration time: more than 6 hours under the above conditions. The calculated values and observed values, which are instantaneous values every hour, are compared using observation station data in domain 2 of each city. Position of measurement sites are shown in Figures 6 and 7. Since the number of measurement sites was limited, observation data in land use other than the urban land use were also used for verification. The calculation accuracies of air temperature and wind velocity at Tokyo, Osaka, Nagoya, Hiroshima, Sendai and Berlin, Essen, Karlsruhe observatories are shown in Tables 2 and 3. For Japanese five cities, calculation accuracy is comparable to previous studies (Kitao et al., 2009 and Moriyama et al., 2014). A comparison of observed and calculated period average air temperatures at the Tokyo, Osaka, Nagoya, Hiroshima, Sendai and Berlin, Essen, Karlsruhe observatories are shown in Figures 8 and 9. The difference was a little large in Sendai, but it was not noticeable in Table 2. It was recognized that the difference was large in Karlsruhe since the comparison could be carried out only in the land use other than urban, while it was done in the urban land use in Berlin and Essen.

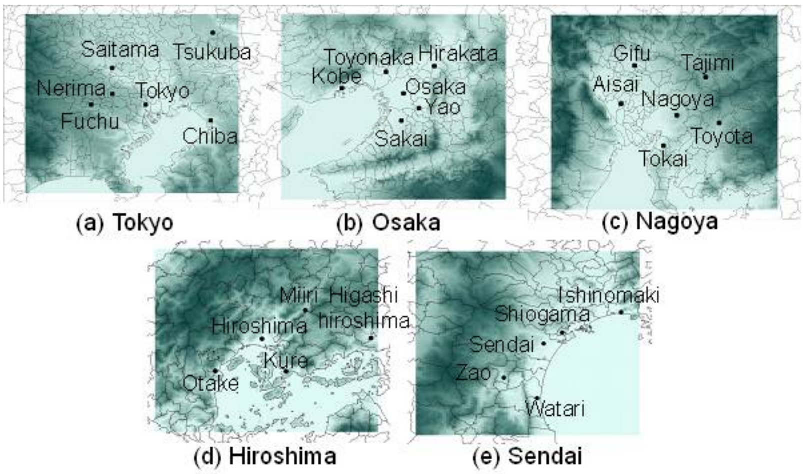

Figure 6. Position of measurement sites in Tokyo, Osaka, Nagoya, Hiroshima, Sendai (103 km square).

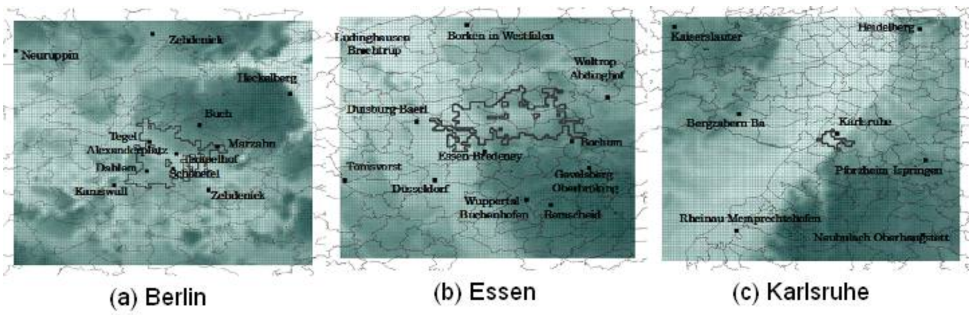

Figure 7. Position of measurement sites in Berlin, Essen, Karlsruhe (103 km square).

Table 2. The calculation accuracies of air temperature and wind velocity for Japanese cities.

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	Temperture	Bias[C]	RMSE[C]	Correlation	Wind speed	Bias[m/s]	RMSE[m/s]	Correlation
Tokyo area	Tokyo	0.50	0.72	0.92	Tokyo	-0.38	0.54	0.78
	Nerima	0.72	0.79	0.92	Nerima	1.74	1.85	0.63
	Fuchu	1.80	2.14	0.90	Fuchu	0.01	0.72	0.70
	Saitama	1.13	1.19	0.91	Saitama	0.41	0.72	0.69
	Tsukuba	0.82	0.88	0.94	Tsukuba	0.73	0.95	0.74
	Chiba	-0.24	0.28	0.90	Chiba	-0.97	1.03	0.78
Osaka area	Osaka	0.20	0.31	0.92	Osaka	-0.13	0.43	0.67
	Kobe	0.30	0.45	0.89	Kobe	-1.14	1.19	0.59
	Sakai	0.40	1.15	0.91	Sakai	0.28	0.71	0.58
	Toyonaka	0.43	0.54	0.91	Toyonaka	-0.18	0.52	0.62
	Yao	0.92	0.98	0.92	Yao	-0.71	0.92	0.56
	Hirakata	0.42	0.63	0.87	Hirakata	0.86	0.94	0.47
Nagoya area	Nagoya	0.71	0.80	0.90	Nagoya	-0.46	0.56	0.64
	Tokai	0.24	0.48	0.89	Tokai	0.97	1.02	0.53
	Aisai	-0.18	0.32	0.93	Aisai	1.37	1.52	0.62
	Toyota	0.59	0.75	0.93	Toyota	0.42	0.58	0.33
	Gifu	0.97	1.01	0.90	Gifu	-0.29	0.40	0.64
	Tajimi	0.47	0.84	0.93	Tajimi	0.46	0.59	0.53
Hroshima area	Hiroshima	0.01	0.02	0.91	Hiroshima	-0.56	0.77	0.56
	Kure	-0.05	0.06	0.93	Kure	0.04	0.55	0.59
	Otake	0.05	0.05	0.86	Otake	-0.70	0.74	0.41
	Higashihiroshima	-0.08	0.08	0.94	Higashihiroshima	-0.50	0.77	0.30
	Miiri	0.03	0.03	0.89	Miiri	-1.38	1.68	0.01
Sendai area	Sendai	-0.03	0.04	0.90	Sendai	-0.19	0.44	0.46
	Watari	-0.06	0.06	0.81	Watari	-0.36	0.62	0.31
	Shiogama	0.47	1.08	0.91	Shiogama	1.38	1.45	0.32
	Zao	-0.02	0.04	0.83	Zao	-0.82	0.90	0.12
	Ishinomaki	-0.05	0.06	0.83	Ishinomaki	-0.74	0.82	0.57

Table 3. The calculation accuracies of air temperature and wind velocity for German cities.

		Temperature			Wind speed		
		Bias[°C]	RMSE[°C]	Correlation	Bias[°C]	RMSE[°C]	Correlation
Berlin area	Alexanderplatz	0.11	0.61	0.93	-	-	-
	Buch	-0.3	0.58	0.93	-	-	-
	Dahlem	1.44	1.84	0.94	-	-	-
	Marzahn	0.47	0.73	0.93	-	-	-
	Tegel	0.59	0.78	0.94	1.29	1.35	0.84
	Tempelhof	0.73	0.84	0.94	0.97	1.08	0.82
	Neuruppin	-0.15	1.27	0.9	2.08	2.14	0.79
	Potsdam	-0.74	1.88	0.91	0.86	0.9	0.74
	Zehdenick	-0.28	0.95	0.91	-	-	-
	Heckelberg	0.02	0.94	0.91	-	-	-
Essen area	Bochum	-0.15	0.73	0.87	-	-	-
	Borken in Westfalen	-0.53	1.84	0.90	-	-	-
	Essen-Bredeney	0.47	0.76	0.92	1.37	1.40	0.74
	Toenisvorst	-0.69	0.95	0.92	-	-	-
	Wuppertal-Buchenhofen	1.19	1.34	0.91	-	-	-
	Remscheid	-0.56	0.82	0.90	-	-	-
	Luedinghausen-Brochtrup	-0.82	0.92	0.92	-	-	-
	Duisburg-Baerl	-1.00	1.32	0.91	-	-	-
	Waltrop-Abdinghof	-0.12	0.45	0.92	-	-	-
	Gevelsberg-Oberbroeking	-0.60	0.88	0.90	-	-	-
Karlsruhe area	Bergzabern-Ba	-1.63	1.70	0.91	-	-	-
	Heidelberg	-2.93	3.00	0.91	-	-	-
	Kaiserslautern	-0.99	1.15	0.93	-	-	-
	Karlsruhe	-1.60	1.73	0.92	-0.54	0.61	0.73
	Pforzheim-Ispringen	-0.13	0.72	0.92	0.46	0.66	0.61
	Rheinau-Memprechtshofen	-0.44	0.71	0.91	-	-	-
	Neubulach-Oberhaugstett	0.12	0.94	0.91	-	-	-

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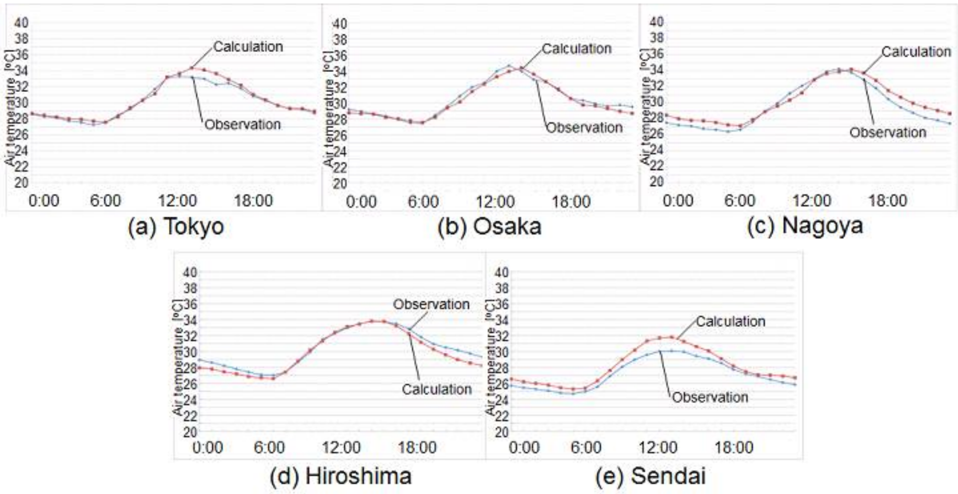

Figure 8. A comparison of observed and calculated period average air temperatures at the Tokyo, Osaka, Nagoya, Hiroshima and Sendai observatories.

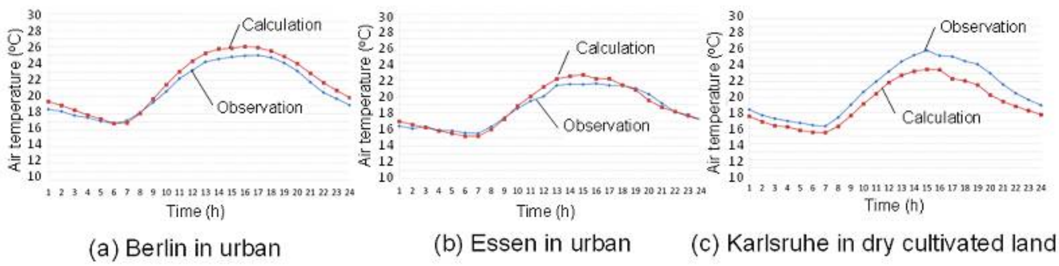

Figure 9. A comparison of observed and calculated period average air temperatures at the Berlin, Essen and Karlsruhe observatories.

4. Analysis on Air Temperature Distribution

Air temperature distribution at 2 m height in Japanese cities, at 14:00, 25 August 2010 is shown in Figure 10. However, it is 7 August only in Sendai, due to weather condition. Air temperature was lower in the coastal areas and higher in the inland areas. Number of higher air temperature points in Tokyo was larger than those in the other cities, which are located mainly in the inland areas. Air temperature distribution at 2 m height at 14:00, in 25 July for Berlin and Karlsruhe, in 24 July for Essen, 2008 is shown in Figure 11. Air temperature was lower in the boundary areas with the suburbs and higher in inner urban areas. Relationship between distance from the coast and air temperature in Japanese cities at 14:00, 25 August 2010 is shown in figure 12. In all five cities, as the distance from the coast increases, air temperature rose. The curve of air temperature rise varies in five cities. It is also different from day to day in a city. It is considered that the cause is the cloud amount during the night and the sea surface temperature during the day. Relationship between distance from the windward boundary with the suburbs and air temperature at 14:00, in 25 July for Berlin and Karlsruhe, in 24 July for Essen, 2008 is shown in figure 13. In all three cities, as the distance from the suburb increases, air temperature rose.

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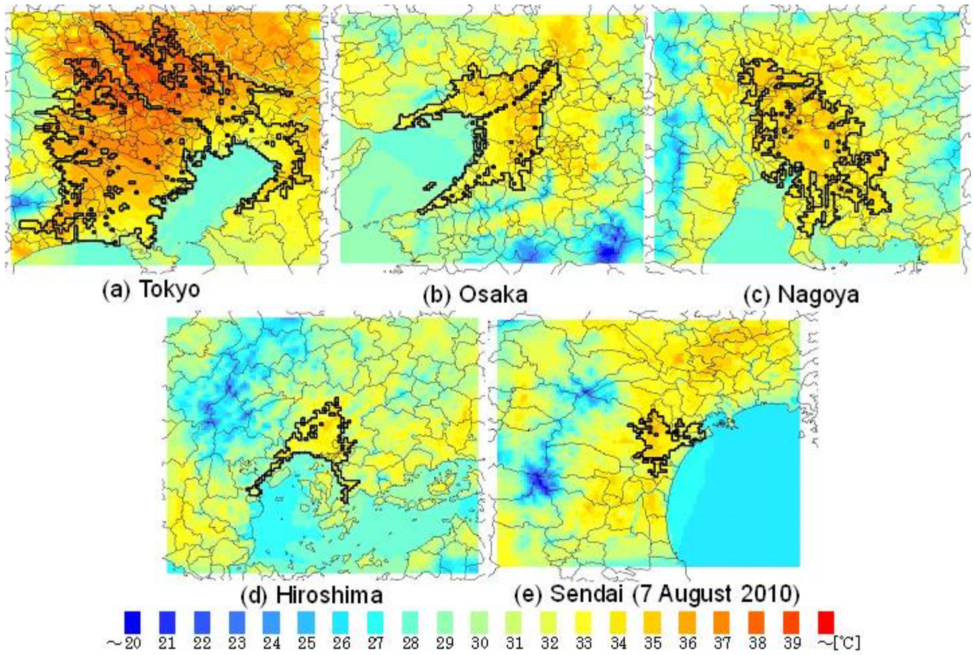

Figure 10. Air temperature distribution at 2 m height in Japanese cities (103 km square).

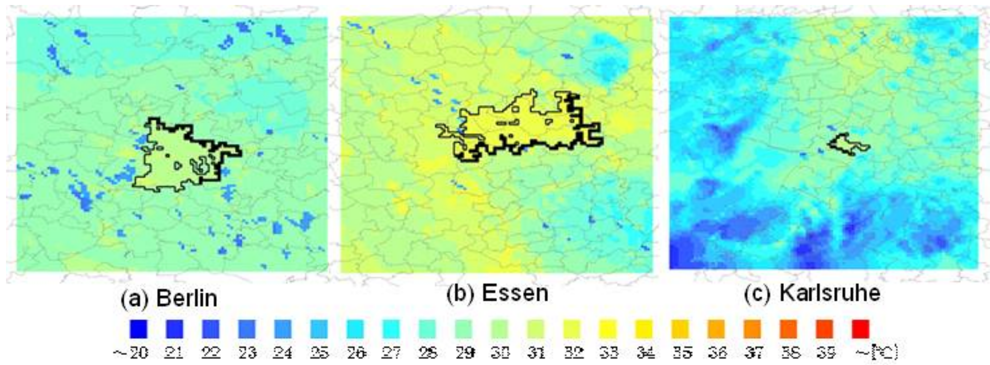

Figure 11. Air temperature distribution at 2 m height in German cities (103 km square).

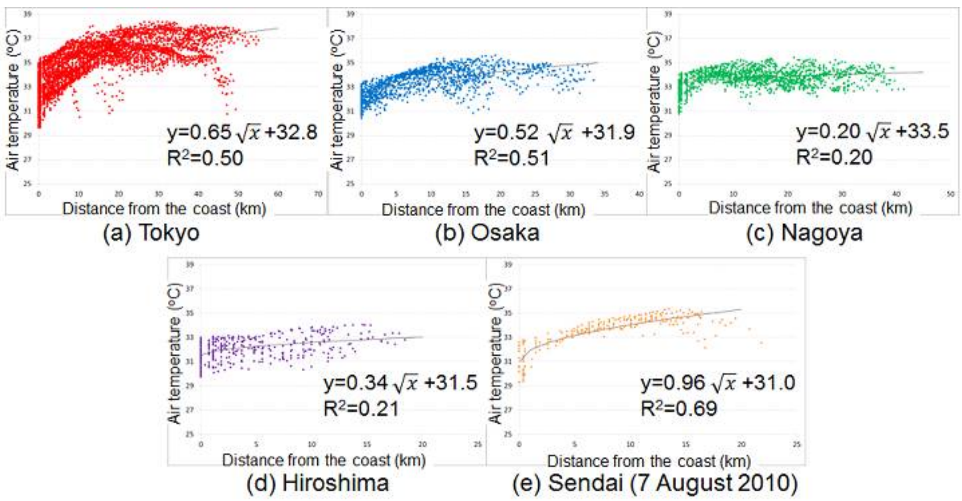

Figure 12. Relationship between distance from the coast and air temperature in Japanese cities.

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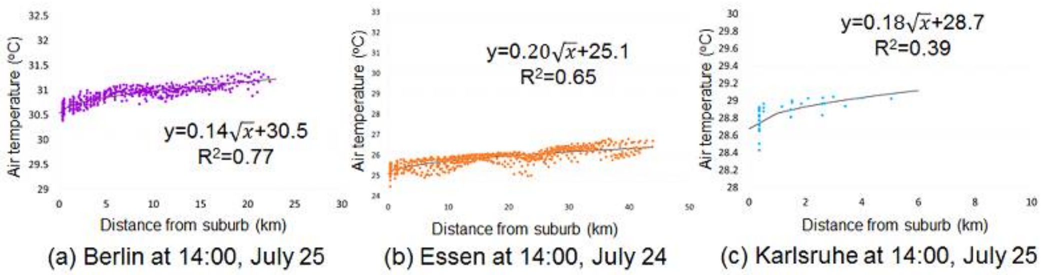

Figure 13. Relationship between distance from the suburb and air temperature in German cities.

Relationship between distance from the coast and air temperature at 14:00 averaged in fine weather condition for Japanese cities is shown in Figure 14. Air temperature rise increases with distance from coast and they are nearly the same in Tokyo and Osaka. Number of higher air temperature points in Tokyo was larger than those in Osaka and Nagoya, which are located mainly in the inland areas. The heat island intensities of Osaka and Tokyo were almost the same at the same distance points from the coast regardless of different urban areas. There is no relationship between city size and air temperature rise. City size is indicated by the distance from the coast to the inland edge of each city as shown in Figure 14; Tokyo 60 km, Osaka and Nagoya 35-40 km, Hiroshima and Sendai 20 km. In Hiroshima, urban area is spreading along coastal line as in Tokyo and Osaka, and inland urban area is less than these cities, where air temperature is a little higher. As a result, the curve of air temperature rise in Hiroshima is smaller than those in Tokyo and Osaka.

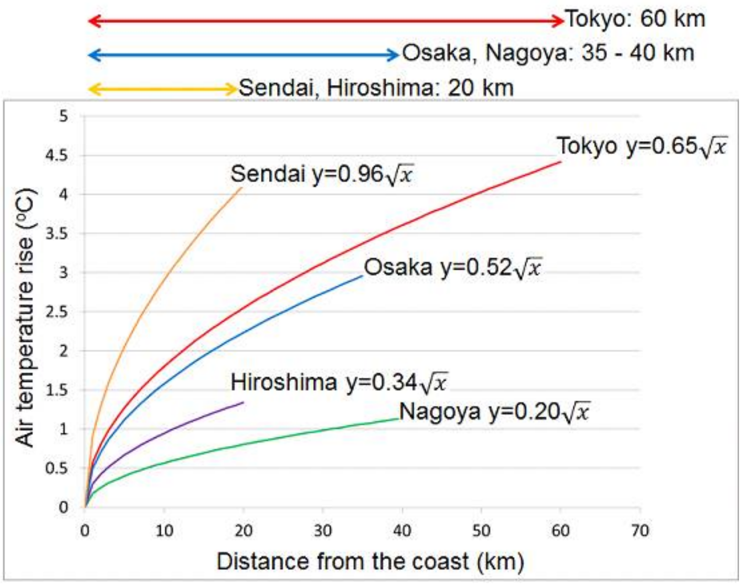

Figure 14. Relationship between distance from the coast and air temperature at 14:00 averaged in fine weather condition for Japanese cities.

Frequencies of air temperature at 14:00 on August 25 and 7, 2010 are shown in figure 15. In these days the cities indicated in the figure were fine and sea breeze condition. In Nagoya and Sendai, the number of urban land use in coastal areas is less than the other three cities, where air temperature is a little lower. As a result, air temperature difference between coastal and inland urban area is small and the curve of air temperature rise is smaller than those in Tokyo and Osaka. In Sendai, air temperature in the inland urban area is the same as in the other cities, but air temperature in the coastal urban area is a little lower than the other cities, due to about 1 degree lower sea surface temperature influenced by the latitude. As a result, air temperature difference between coastal and inland urban area is large and the curve of air temperature rise is larger than those in Tokyo and Osaka. As described above, coastal land use has a large influence on air temperature rise.

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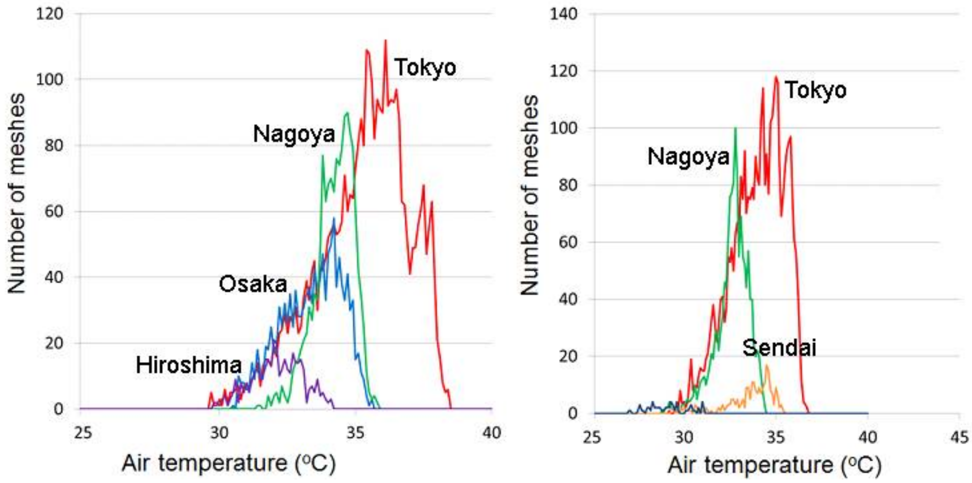

Figure 15. Relationship between distance from the coast and air temperature at 14:00 averaged in fine weather condition for Japanese cities.

5. Discussion

Distance from boundary and air temperature rise in Tokyo, Osaka, Nagoya, Berlin, Essen, Karlsruhe is shown in Figure 16. Air temperature rises in three German cities are almost the same as that in Nagoya. The development of the urban boundary layer is expressed by following equation (1), if the advection by the sea breeze is dominant, as a function of the distance from the boundary L (m).

$$\Delta T = \sqrt{\frac{2(1+k)HL\alpha}{C_p \rho U}} \tag{1}$$

where k is the ratio of entrainment (0 to 1), H is the sensible heat flux from the ground surface (W/m^2), which is calculated reflecting the advection effect on upper air by the sea breeze, α is air temperature gradient (K/m), C_p is the specific heat of air (=1000 J/(kgK)), ρ is air density (=1.2 kg/m^3), and U is wind velocity (m/s). Assuming $\alpha = 0.006$ (K/m), it becomes following equation (2).

$$\Delta T = (0.0032 \sim 0.0045)\sqrt{H/U}\sqrt{L} \tag{2}$$

Assuming $H = 150$ (W/m^2), $U = 5$ (m/s), it becomes following equation (3).

$$\Delta T = (0.55 \sim 0.78)\sqrt{x} \tag{3}$$

where x (= 1000L) is the distance from the boundary (km). Air temperature rises in Tokyo and Osaka are almost consistent with equation (3). Approximate curves of air temperature rise of each day in fine days in German cities are shown in Figures 17. Although the distance from the inflow boundary to the outflow points in urban area differs according to the wind direction, they are almost 15 km in Berlin and Essen, 5 km in Karlsruhe. In three German cities, the urban boundary layer may not develop sufficiently because the fetch distance is not enough.

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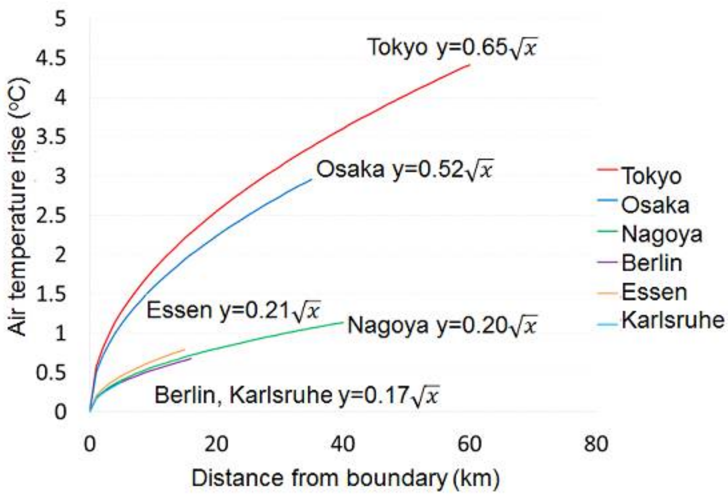

Figure 16. Distance from boundary and air temperature rise in Tokyo, Osaka, Nagoya, Berlin, Essen, Karlsruhe.

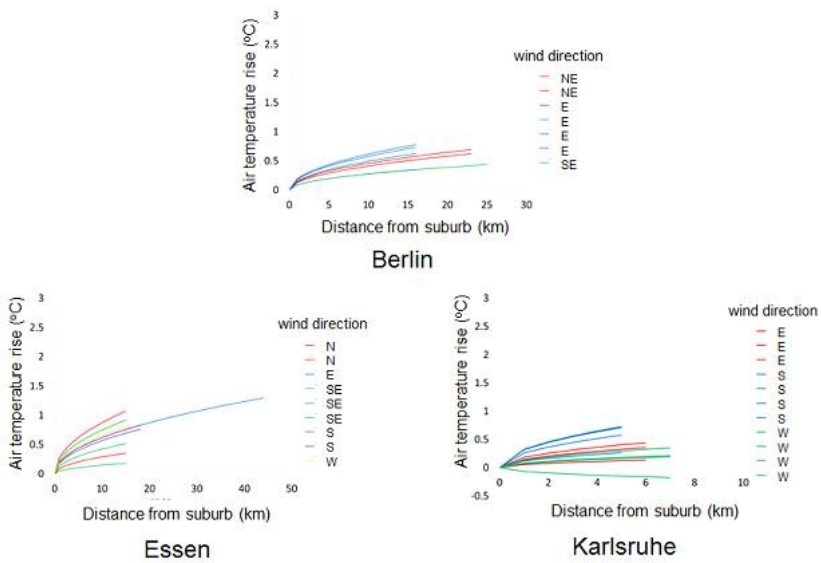

Figure 17. Approximate curves of air temperature rise of each day in fine days in German cities.

6. Conclusions

The relationship between city size, coastal land use and air temperature rise with distance from coast during summer day is analyzed using the meso-scale Weather Research & Forecasting (WRF) model in five coastal cities in Japan with different sizes and coastal land use (Tokyo, Osaka, Nagoya, Hiroshima and Sendai). In addition, the similar analysis is carried out for inland cities (Berlin, Essen and Karlsruhe in Germany). Air temperature increased as distance from the coast / the suburb increased, reached its maximum, and then decreased slightly. Air temperature rise increases with distance from coast and they are nearly the same in Tokyo and Osaka. Number of higher air temperature points in Tokyo was larger than those in Osaka and Nagoya, which are located mainly in the inland areas. The heat island intensities of Osaka and Tokyo were almost the same at the same distance points from the coast regardless of different urban areas. There is no relationship between city size and air temperature rise. In Nagoya and Sendai, the number of urban land use in coastal areas is less than the other three cities, where air temperature is a little lower. As a result, air temperature difference between coastal and inland urban area is small and the curve of air temperature rise is smaller than those in Tokyo and Osaka. In Sendai, air temperature in the inland urban area is the same as in the other cities, but air temperature in the coastal urban area is a little lower than the other cities, due to about 1 degree lower sea surface temperature influenced by the latitude. Coastal land use has an influence on air temperature rise. In three German cities, the urban boundary layer may not develop sufficiently because the fetch distance is not enough.

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