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Idealized experiments on the development of urban warming under various geographical conditions using a meso-scale meteorological model

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1. Introduction

Geographical characteristics make a distincitive local circulation for each characteristic, for example sea breeze. Effects of the circulation around an urban area on a diurnal change of urban atmosphere have been well discussed with observations and numerical simulations.

The circulation would also affect a long-term climate change over the city. Because the characteristics vary urban effects, a various climate change is shown depending on the characteristics even if cities have a same rate of urbanization. Relationship between urban warming and a geographical characteristic around the city has been investigated by analyses on the long-term observation data (Park et al. 1994; Fujibe 1995; Ito et al. 2014). In addition, Kusaka et al. (2000) have simulated the atmosphere over a coastal city, Tokyo, with a land-use in three periods, and Sasaki et al. (2005) have compared heat balances among real cities which assume an urban development of a costal city. These studies have suggested that urban warming over a long term is dependent on the geographical characteristics, and interaction between urban temperature and sea breeze changes as urban develops for a coastal city.

There are some studies about the climatological change on an urban area with taking into account geographical effects as described above, but it is insufficient comparing with the geographical effects on the diurnal change. It is because how a mechanism which caused the different trend of urban warming among different geographical characteristics, and how the effect of the characteristic on the urban warming are uninvestigated.

In this study, idealized numerical experiments were conducted to understand urban warming with various geographical characteristics using a meso-scale meteorological model. Urban areas with three different stages of urbanization were set up to describe the urban development, and they are under three simple geographical conditions: an inland city, a coastal city and a basin city. For each city, we simulated the diurnal variation of the meso-scale atmosphere in summer and winter cases and discussed the effect of geography on the trendency of warming with urbanization.

2. Methodology

2.1 Model outline

Used model is a nonhydrostatic model developed by the Japan Meteorological Agency (JMA-NHM) (Saito et al. 2006). Model version is JMA-NHM (2012-12-04). We simplify the atmospheric condition at an initial time, representation of urban development, and geographical condition to focus on a general characteristic of urban warming.

The experimental domain is 400 x 400 on inland cities, 720 x 400 on coastal cities and 500 x 500 on basin cities with a horizontal spacing of 1 km. A total of the vertical layers is 50 up to 21801 m with the depth of 40 m in the bottom layer and 886 m in the top layer. Time step of calculation is five seconds. The latitude, 36.0ºN, decides the duration of sunshine, 04 LST to 20 LST in summer and 07 LST to 18 LST in winter. Coriolis force is neglected because the effect of force is insignificant on the urban warming and local circulation which are focused in this study. Yoshikado (1992) and Ganbat et al. (2014) also leave the force out of account.

Land-use on a lower boundary consists of three classes; urban area, green field and water field. Surface parameter is given on Table 1.

Table 1 Surface parameters.

		Urban area	*Green field*	*Water field*
Roughness [m]	Summer	2.7	1.2	0.001
	Winter	2.7	1.1	0.001
Evaporation	Summer	0.029	0.52	1.0
	Winter	0.029	0.30	1.0
Albedo		0.21	0.19	0.10
Thermal diffusion coefficient [10^{-6} m^2 s^{-1}]		1.5	0.57	1.3
Thermal content [J m^{-3} K^{-1}]		2.0	1.7	1.9

Geographical characteristics are divided into three conditions; an inland, a coastal and a basin. Inland city locates a city on a flat green plain field, coastal city is in contact with a coastline, and basin city is surrounded by mountains. Coastal cities exist to contact a coast regardless of the size of city. Water field set 250 x 400 in the simulated domain, 720 x 400. Shape of mountains for basin city indicates,

$$h = \begin{cases} 1 + H_m \sin^2\{(l - r_b)\dfrac{\pi}{2W_m}\} & (r_b < l < r_b + 2W_m) \\ 1 & (l \le r_b,\ r_b + 2W_m \le l) \end{cases}.$$

Here h [m] is the height of a point with the horizontal distance from the center of the basin bottom, l [km], H_m is the mountaintop, W_m is the half width of the mountains and r_b is the radius of the basin bottom. This experiment uses H_m = 1500 m, W_m = 30 km, r_b = 20 km. Slope angle of the mountains is about 2.9°.

2.2 Urban development

Urbanization represents in three steps; a small city, a middle city, and a large city. As increasing the size of city, a growth of building and an increase of anthropogenic heat make progress. An urban canopy scheme is performed on grids with land-use of urban. The scheme is a single-layer square prism urban canopy (SPUC) scheme (Aoyagi and Seino 2011). Anthropogenic heat is estimated with large scale urban consumption of energy (LUCY), version 3.1 (Allen and Grimmond 2011). Information about urban area is summarized in Table 2.

Table 2 Urban parameters.

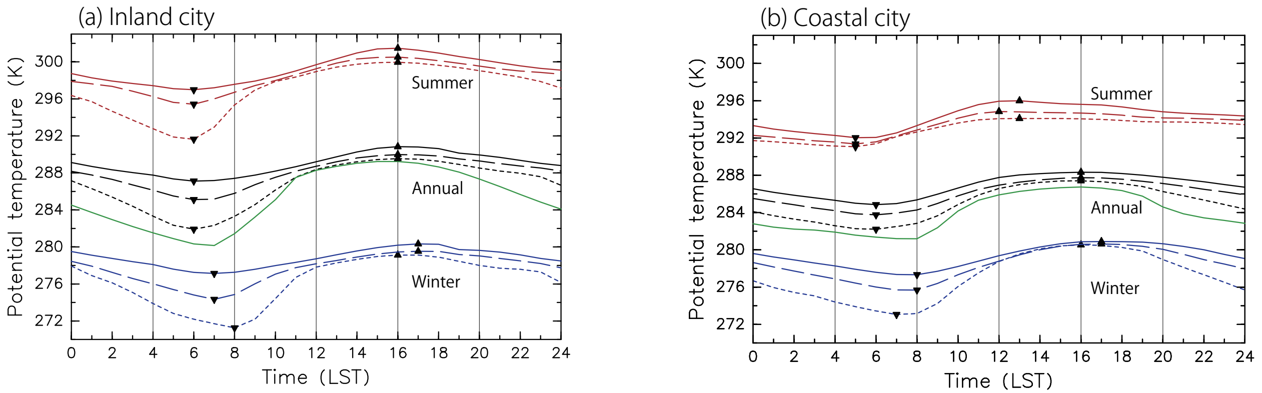
Size of city		**Small**	**Middle**	**Large**
Radius of urban area [km]		5	10	20
Building height [m]		7	12	14
Building weight [m]		10	10	10
Building height		0.4	0.6	0.7
Anthropogenic heat (daily mean) [W m^{-2}]	Summer	7.5	34.6	69.2
	Winter	6.5	28.4	57.5

2.3 Design of experiments

We conducted a total of 10 experiments for summer and winter. Initial time was set every three hours from 18 LST and five members run for each season. The integral time was from 54 hours for the run from 18 LST to 42 hours for that from 06 LST, and the analyzed period was an ensemble mean time series of the last 24 hours for each runs.

Initial condition was the lapse rate of potential temperature of 5 K km^{-1}, wind velocity of 0 m s^{-1}, humidity of 0%, and surface pressure of 1000 hPa. Sea surface temperature in summer and winter fixed with 20ºC and 15ºC, respectively. Initial surface temperature at the level of 20 m was a 30-yr average value over 17 sites in Japan. These sites were selected by JMA to estimate climate change in Japan. Each seasonal value was an average for June to August in summer and December to February in winter. The temperatures at initial times, 18 LST, 21 LST, 00 LST, 03 LST, and 06 LST, were 24ºC, 22ºC, 22ºC, 21ºC and 21ºC in summer, and 5.5ºC, 4.5ºC, 3.5ºC, 3.0ºC, 2.5ºC in winter. Seasonal results are indicated using the averaged over each five members, and annual results using the averaged over the total of 10 members.

Representative temperature of each city is defined as an averaged temperature over the inside of the urban area, and is described as an urban temperature in the following. Here, the inside area for the middle city is the area with the radius of 5 km from the center of urban area, and is less affected by the surroundings. Similarly, the inside area is that with the radius of 3 km for the small city, and 10 km for the large city.



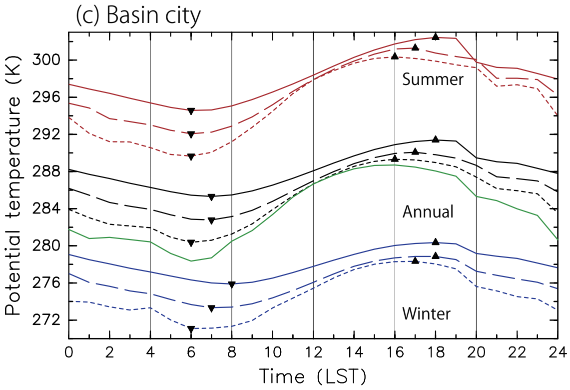


Fig. 1 Diurnal variation of urban temperature. Black line is an annual average of urban temperature. Red and blue lines are urban temperature in summer and winter. Green line is an annual average of temperature over green fields. Solid, dashed and dotted lines indicate the large city, the middle city, and the small city, respectively. ▼ means the daily minimum temperature, and ▲ means the daily maximum temperature.

3. Results

3.1 Diurnal variation of urban temperature

Figure 1 shows the diurnal variation of urban temperature for each geographical condition. The temperatures are at 20 m height. General characteristics of urban climate can be seen as a larger rising of the daily minimum temperature than that of the daily maximum temperature except the coastal cities in summer. The diurnal ranges on the urban exist smaller than on the green.

Diurnal variation of annual temperature for the inland cities shows that the increase amounts on the mean temperature and the daily minimum temperatures are larger at the primary stage, from the small city to the middle city, than at the secondary stage, from the middle city to the large city (Fig. 1a, Annual). It means that the warming is decelerated. The difference in the amount between the stages is 1.2 K on the daily minimum temperature. On the other hand, the amount on the daily maximum temperature is smaller at the primary stage: the warming is accelerated.

Diurnal temperature range for the coastal cities is the smallest in summer among that for all cases (Fig. 1b, Summer). It is a notable characteristic that the range becomes large as the city develops. The rising is larger on the daily maximum temperature than on the daily minimum temperature in both stages. This is an opposite characteristic of a general urban warming. The increase amount at the secondary stage is more than 0.3 K larger than that at the primary stage for mean temperature and the daily minimum and maximum temperatures. The tendency of warming is acceleration. The daily maximum temperatures are similar for the different size of city in winter (Fig. 1b, Winter). The increase amount of daily minimum temperature is larger in winter than in summer. The mean temperature and the daily minimum temperature indicate a large increase at the primary stage relative to the secondary stage.

Diurnal variation of annual temperature for the basin cities indicates that the increase amount at the secondary stage is larger than that at the primary on the mean temperature and the daily maximum and minimum temperatures (Fig. 1c, Annual). Thus, the warming is accelerated. The increase amounts are the largest on the daily minimum temperature, but the difference of the amounts between the stages is the largest on the daily maximum temperature.

The temperature change rate from hour to hour is large for the basin city comparing with that for the inland city except a similar rate from the midnight to the early morning. Only the diurnal variations for the basin cities have a discontinuous period around the late of afternoon. The period is from 21 LST to 23 LST for the small and middle cities and from 20 LST to 22 LST for the large city. The discontinuity for the large city occurs 1-hr earlier than the small and middle cities. The small city has the discontinuity from 02 LST to 04 LST as well. The discontinuous period is observed by Park (1987).

The difference between the geographical conditions appears clearer in winter than in summer. The maximum of diurnal range appears on the basin cites in summer, and on the other hand there is little to distinction among the ranges in winter. The maximum of the mean temperature is recorded in the inland cities. The temperatures in the coastal cities keep lower throughout the day.

3.2 Causes for the warming trend on the daily maximum and minimum temperature

3.2.1 Inland city

The warming on the daily maximum temperature is accelerated because the increase amount of the urban temperature from the middle city to the large city is larger than the amount from the small city to the middle city as already described above. When the daily maximum temperature is recorded, mixing layers form up to more than 1000 m height over the urban area for the cities with the different size (not shown). Therefore, it is difficult that an increasing heat from the urban with the urbanization causes the temperature change because the atmosphere is well disturbed with a thick layer.

Heat island circulation (HIC) appears at 11 LST around the edge of all cities. Vertical structure of vertical wind is illustrated in Fig. 2. HIC forms when the temperature rising on the green fields starts moderating at 11 LST, and thus the temperature difference increases between the urban area and the surroundings (Fig. 1a, Annual). Upward flow of the circulation forms around the edge of the urban area, like a sea breeze front. HICs get significant over the edge regardless of the size of city at 12 LST (Fig. 2a), and then the circulations begin moving towards the center of urban area (Fig. 2b). The circulation brings cool air over the surroundings to the urban. The temperature rising moderates from the time of the circulation reaching to the inside of the urban area. The timing is 12 LST for the small city, and then 15 LST for the middle city. In contrast, the temperature still keeps rising on the large city at 15 LST because the circulation exists out of the inside of the urban area. Therefore, as the city enlarges, it takes more time for the penetration of the circulation to the inside of urban, and that is to say, the temperature more increases. For this reason, the rise of daily maximum temperature increases with an urban expansion.

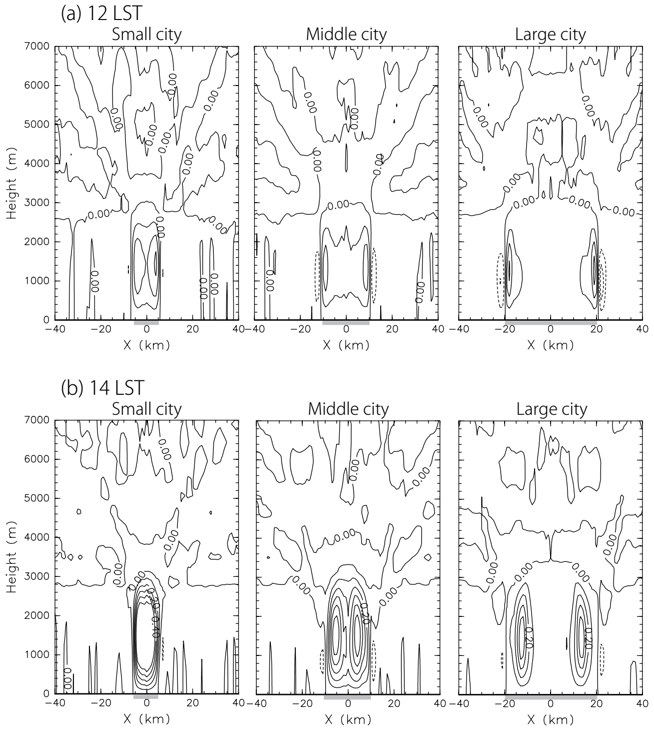


Fig. 2 Vertical structure of vertical wind over the inland city during the daytime [m s^{-1}]. (a) 12 LST, (b) 14 LST. The wind is annual value. Contour interval is 0.1 m s^{-1} between -0.5 m s^{-1} and 0.5 m s^{-1}. Gray line at the bottom of each panel indicates the urban area.

3.2.2 Coastal city

In the coastal cities, the trend of warming is acceleration in summer. Figure 3 indicates the vertical profiles of potential temperature around the time of the daily maximum temperatures recorded in summer. The temperature is the average over the analyzed area including the contact point of the urban and the coast and the center of urban area. The temperature is constant in the layer with approximately 600 m thickness from the surface and the layer from 1000 m to 1600 m, and the air between these layers is stably stratified. There is a significant difference of temperature among the cities under the stable layer. The stability of the air between the two mixing layers is more close to a neutral on the large city.

The height of the mixing layers over all coastal cities is about 600 m and this thickness of the layer corresponds to the depth of sea breeze, that is, sea breeze controls the thickness of the mixing layer in the coastal city. The

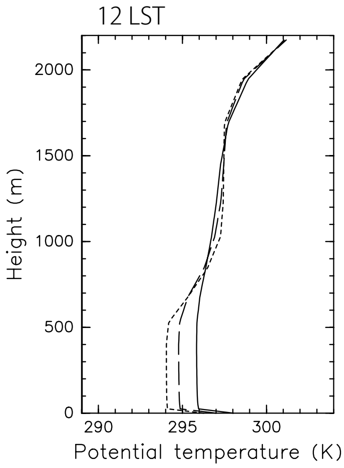


Fig. 3 Vertical profiles of potential temperature over the analyzed area of costal cities at 12 LST in summer [K]. Solid, dashed, and dotted lines mean the large city, the middle city and the small city, respectively.

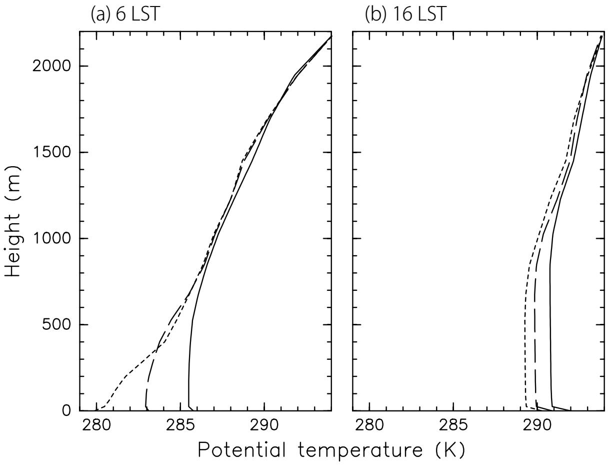


Fig. 4 Same as Fig. 3, except for the annual mean temperature for the basin city at (a) 06 LST and (b) 16 LST.

thickness represented in this experiment is comparable to that by observations (Ohashi and Kida 2001). Because the sensitive heat which increases with the urban development diffuses in the same thickness of the layer among the cities, urban temperature more rises in a larger city.

The variation in Fig. 1b indicates that the daily maximum of urban temperature in the costal city is 5 K less than that in the inland city due to a cool air by sea breeze in summer. However, the increase amounts from the small city to the middle city and from the middle city to the large city are larger in the costal city. The difference in the amount between the costal and inland cities extends from the primary stage to the secondary stage from 0.26 K to 0.4 K.

Sea breeze is an important factor for the large increase amount of urban temperature with an urbanization during the daytime and for resulting in more accelerated warming comparing with the inland city. However, a change of the daytime temperature even for a city existing close to the coast is corresponding to the temperature change in the inland city until the sea breeze reaches over the city. The daily maximum temperature is recorded at 16 LST in the inland city (Fig. 1a, summer), and the sea breeze front in the case without an urban area locates around 50 km from the coast at the time (not shown). Therefore, a city which locates more than 50 km far from the coast could have a high urban temperature and a small increase amount of the temperature with urbanization like the inland city, and in contrast, a city within 50 km from the coast could have a feature in the coastal city.

3.2.3 Basin city

In the basin city, the warming trend is accelerated on the mean temperature and the daily maximum and minimum temperature. Figure 4 indicates the profiles of potential temperature averaged the inside of urban area at 06 LST and 16 LST. Stable stratification exists more than about 500 m height over all cities at 06 LST, and especially in the small city over which the stratification continues on the surface (Fig. 4a). The lapse rate gets to be small near the surface as the city develops. The difference is clear under 400 m between the small city and the middle city, and under 800 m between the middle city and the large city. Therefore, urban development has effects on the layer with 800 m thickness in the early morning. In the inland city, the strong stable layer forms at 300 m depth from the surface over the small and middle city. In addition, the nearly neutral layer exists over the stable layer of the small and middle cities and over the large city up to 1000 m and over (not shown). Therefore, when the urban heat vanishes the strong stable layer and then the deep neutral layer builds as seen over the large city, the temperature rise becomes small. By contrast, over the basin city, a cold air pool remains in the basin and there is no neutral layer except over the large basin city from the surface to the height of about 400 m. The profile of temperature gets a neutral with the urban development, but the depth of the neutral layer is shallower even over the large basin city than over the large inland city. Therefore, the warming in the secondary stage is as significant as that in the primary stage unlike the warming in the inland city.

At 16 LST, mixing layers grow up for every city up to approximately 1000 m (Fig. 4b). Comparing with the atmosphere at the higher level than the top of mountains, the stability from 1000 m to 1500m is relatively strong. The layer is the nocturnal stratification, and remains over the city inside of basin even during daytime. Due to the stable layer over the cities, the mixing layer exists with a two-thirds height of the layer in the inland city, and thus the temperature is easy to rise. The existence of city helps the stagnation of the stable layer in the basin. Whiteman and McKee (1982) and Whiteman et al. (2004) explain the vanishing process of a cold air pool in a basin without an urban by numerical simulations and observation. The air in the cold pool starts mixing around the bottom of basin and the slope after sunrise. And the subsiding flow which is caused by an upslope wind results in a depression of the cold pool, and not only works as a heating on the bottom of basin. And then, the pool gradually disappears. This simulation with an urban area indicates that HIC prevents developments of the subsiding flow and an appearance period of the flow is short, especially on the large city. Therefore, an influence of the subsiding flow on the cold pool becomes weak with the urban development and the stable layer still remains in the daytime even when the urban heating increases with the urban developments. Due to the existence of the stable layer over the cities and, additionally, the delay of penetration of HIC to the center of the basin city, the increase amounts in the both stages is larger in the basin city than in the inland city and the amount at the primary stage is larger than that at the secondary stage: the warming shows an acceleration.

4. Conclusion

To investigate the characteristics of urban warming with urban development for each geographical condition, idealized experiments are conducted on three different sizes of city with three different geographies. The tendency of urban warming with urbanization has features for each geography. There is a possibility on that the characteristics actually occur because the numerical results for the middle size of city shows comparable in characteristics to real cities qualitatively. Finally, an analysis toward the discontinuous period in the diurnal variation of urban temperature for the basin city is beyond the scope of this work. However, we have discussed that the relationship between HIC and the downslope wind causes the period.

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