Effect of urban block geometry on surface wind and air temperature over a sandbank in the central area of Osaka city, Japan

Turbulence, Heat and Mass Transfer 9

Effect of urban block geometry on surface wind and air temperature over a sandbank in the central area of Osaka city, Japan

A. Yoshida[1] and R. Yasuda[2]

[1]*Department of Mechanical Engineering, Osaka Prefecture University, 1-1 Gakuen-cho, Naka-ku, Sakai, Osaka, 599-8531, Japan.* ayoshida@me.osakafu-u.ac.jp

[2]*Department of Mechanical Engineering, Osaka Prefecture University, 1-1 Gakuen-cho, Naka-ku, Sakai, Osaka, 599-8531, Japan.* yasuda@me.osakafu-u.ac.jp

Abstract – To investigate the influence of urban block geometries on wind and air temperature in a sandbank area in mid-summer, high-resolution analyses were conducted using a meteorological model. Low building density contributes to the ventilation of the study area. The large sky view factor decreases the air temperature at night, while increasing surface temperatures on the ground and buildings in the daytime. However, the air temperature in the daytime is not significantly influenced because the sensible heat from urban surfaces is diluted in a mixed layer, with significant ventilation partly suppressing the air temperature increase. Therefore, the influence of urban block geometry on air temperature is considerably lower than that on the wind. The influence of rivers on the ventilation in the sandbank is much less than that of the urban block geometries. The cooling effect of the rivers in the daytime is comparable to the change in radiative cooling caused by sparse urban blocks.

1. Introduction

Thermal environments near the ground are strongly affected by surrounding features such as buildings, roads, rivers, and parks. In urban areas, particularly where buildings are numerous, urban canopies significantly affect the surface heat budget of the ground. The ventilation efficiencies of urban blocks depend strongly on their geometry (Kubota et al., 2000, Takebayashi et al., 2009, Wong et al., 2010) because wind speed is intensified or weakened by building-induced eddies and drag forces. Therefore, the cooling effect of a sea breeze may differ in magnitude even within a small area, and the air temperature distribution will show complex patterns.

Osaka is the most populous metropolitan area in western Japan and is well known for its severe summertime thermal environment (Kono et al., 2000). The local government of Osaka city has used the “ventilation path” (in Japanese, Kaze-no-Michi) concept to create a future urban plan for the area (Osaka city, 2011) that will mitigate its severe summertime thermal environment by utilizing the cooling potential of the sea breezes from Osaka Bay.

To clarify the effect of urban block geometries on local meteorological fields, we investigated the distribution of wind and air temperatures near the ground surface in Nakanoshima district on a mid-summer day. Nakanoshima district is a representative business area in the central part of Osaka megacity, Japan. In the district, huge buildings are sparsely located, therefore, the urban canopy effect in this area is small. Mobile observations (Yoshida et al., 2012) suggest that the air temperature in Nakanoshima district is slightly cooler than its surrounding area in the daytime. However, it is not clear how much the urban block geometry influences the local climate in the district.

In this study, we newly estimate the urban parameter values in Nakanoshima district to reflect actual condition. High-resolution analyses are conducted out using a meteorological model, and the air temperature results are compared with the mobile observation results mentioned above. The relationship between urban block geometry and the cooling effect of sea breeze is discussed, as is the influence of rivers surrounding the district.

The paper is organized as follows. Section 2 describes the study area and the conditions of the numerical simulation. Model validation and comparison with the observations, the results of sensitivity analyses on the urban parameters, and the influence of rivers in the area are presented in Section 3. The final section presents the conclusions.

2. Method

2.1 Study area

Figure 1 (a) shows the location of Osaka. Because Osaka Plain is bordered by mountains to the north, east, and south, the westerly sea breezes from Osaka Bay in the daytime are expected to mitigate the high temperatures in the plain. Fig. 1 (b) shows Nakanoshima district (enclosed by the yellow line) and its surrounding area. Nakanoshima, which means "middle island" is located at the center of Osaka urban area and is enclosed by two rivers on its northern and southern sides. The central to western part of Nakanoshima district is occupied by large high-rise facilities, whereas the eastern part consists of high- and mid-rise buildings and green parks. The outskirts of the district on both the northern and southern ends consist of dense built-up areas comprising mid-rise office buildings. The study area is fairly flat and lies at 0–3 m above sea level.

2.2 Numerical model and calculation conditions

The Weather Research and Forecasting (WRF) modeling system ver.3.7.1 (Skamarock et al., 2008) was used to simulate the land–sea breeze circulations in the analysis domain (Fig. 2). To obtain the resolutions of the rivers adjoining the district, five domains were set in a two-way nesting configuration. The horizontal resolutions of the outermost domain (D1) and the innermost domain (D5) were 3000 m and 37 m, respectively. The model settings of our numerical experiments are shown in Table 1. The mesh data of altitude and land use, at 50-m and 10-m resolutions, respectively, were obtained from the National Land Numerical Information database. The mesh data of anthropogenic sensible heat estimated by Shimoda et al. (2002) was given within a 100-km square area, which almost coincides with the D2 domain. The depth of the lowest layer was approximately 60 m.

In the simulation, a single-layer urban canopy model (UCM; Kusaka, 2004) implemented in the WRF model was applied to grids in which the land use category was classified as "urban." The UCM assumes two-dimensional street canyons and considers shadowing from buildings; reflections of shortwave and longwave radiation; the wind profile in the canopy layer; and heat transfer for roofs, walls and road surfaces. In the UCM, urban block geometry is put into urban parameters such as building coverage ratio, mean building height, standard deviation of the building heights, building surface ratio, urban fraction, and frontal area index. As shown in Table 2, the WRF system classifies "urban" areas into three types: low-intensity residential, high-intensity residential, and industrial or commercial. For each of the types, the urban parameter values are assigned according to the urban block geometries predefined in the system. These parameters affect heat and momentum fluxes in the bottom layer of the meteorological model as a function of the UCM. The most highly developed areas are classified as "industrial and commercial." According to the land use data we employed, most of the urban grids around Nakanoshima district are categorized as "industrial or commercial." In the outskirts of the district, the actual values of urban parameters are close to that category. In Nakanoshima district proper, however, the buildings are huge and sparsely arranged in comparison with the "industrial and commercial" category. Therefore, the effect of urban block geometry in this district on local meteorological fields will differ from those in the surrounding areas.

We estimated the urban parameter values in Nakanoshima district to reflect actual conditions, and we conducted two cases. For the control run (CNTL), the urban parameters were obtained from the default setting of the WRF system according to their urban category. As previously stated, most of the urban grids around Nakanoshima district were categorized as "industrial or commercial." To investigate the influence of urban block geometry on the meteorological field, we newly estimated the urban parameters in Nakanoshima district (A and B in Fig. 1) based on detailed city block information from "Osaka City Mesh Data (2005)" provided by the Planning and Coordination Bureau of Osaka City, and we conducted a revised (REV) run. In the district, the widths and heights of the buildings were larger, the building density was lower, and the sky view factor was larger than those in the surrounding areas (i.e., "industrial or commercial"), as shown in Table 2. The difference occurred in the urban

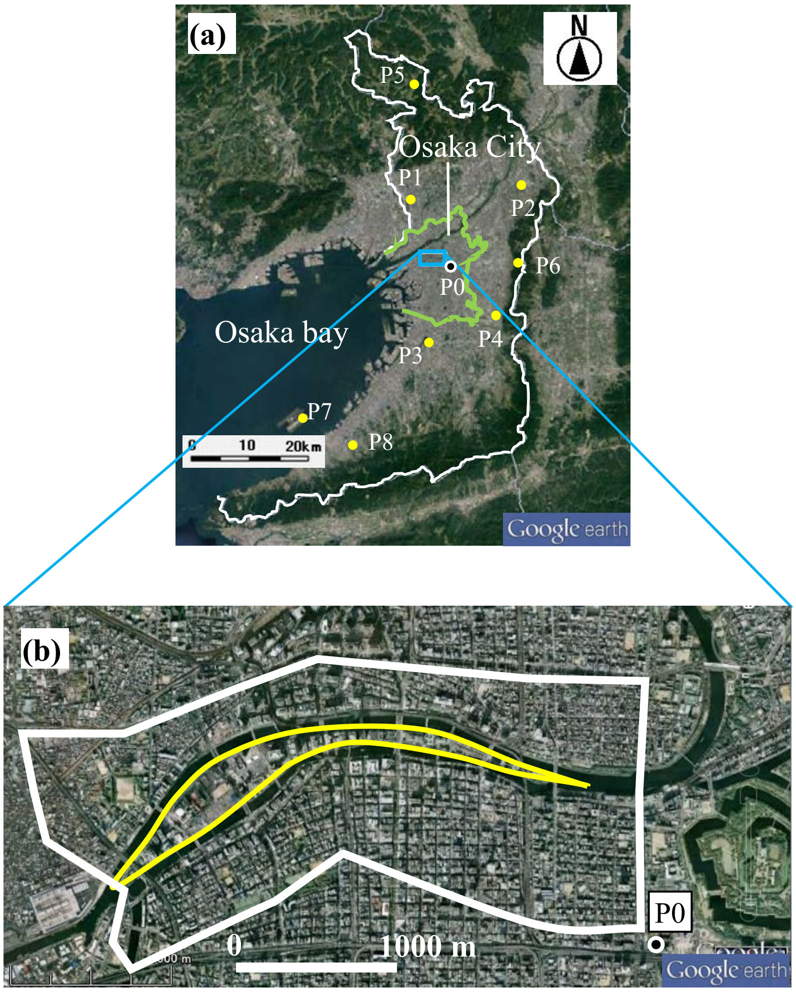

Figure 1 Maps of the study area. (a) Geographic features of Osaka area. White and green lines are the borders of Osaka Prefecture and Osaka City, respectively. P0–P8 are surface monitoring stations operated by Japan Meteorological Agency. (b) Close-up view of the study area. Nakanoshima district and the mobile observation area are enclosed in yellow and white lines, respectively.

parameter values only. For the outskirts area of the district, the urban parameter values were identical ("industrial and commercial") in both the CNTL and REV cases.

In addition to these cases, we conducted another simulation to investigate the influence of rivers surrounding Nakanoshima district on wind and temperature in the study area. In this case (RF case), river grids in the D5 domain except around the northwest corner were reclaimed; that is, the physical processes in the soil layer were activated. In addition, their urban category was altered to "industrial or commercial." The alternation in land use category was made only in D4 and D5 domains because the rivers were not resolved in the D1–D3 domains.

Table 1 Model settings of the numerical experiment.

Domain	D1	D2	D3	D4	D5
Horizontal grid interval (m)	3000	1000	333	111	37
Number of horizontal grids (E–W × N–S)	120 × 120	103 × 103	91 × 52	130 × 79	121 × 91
Central coordinate (lat.,long.)	(34.672°, 135.480°)				
Number of vertical layers	30				
Microphysics	WSM-3 class				
Planetary boundary layer	MYNN level 2.5				
Surface layer	M–O similarity theory				
Longwave radiation	RRTM scheme				
Shortwave radiation	Dudhia scheme				
Land surface model	Noah LSM				
Urban surface model	Single Layer UCM				

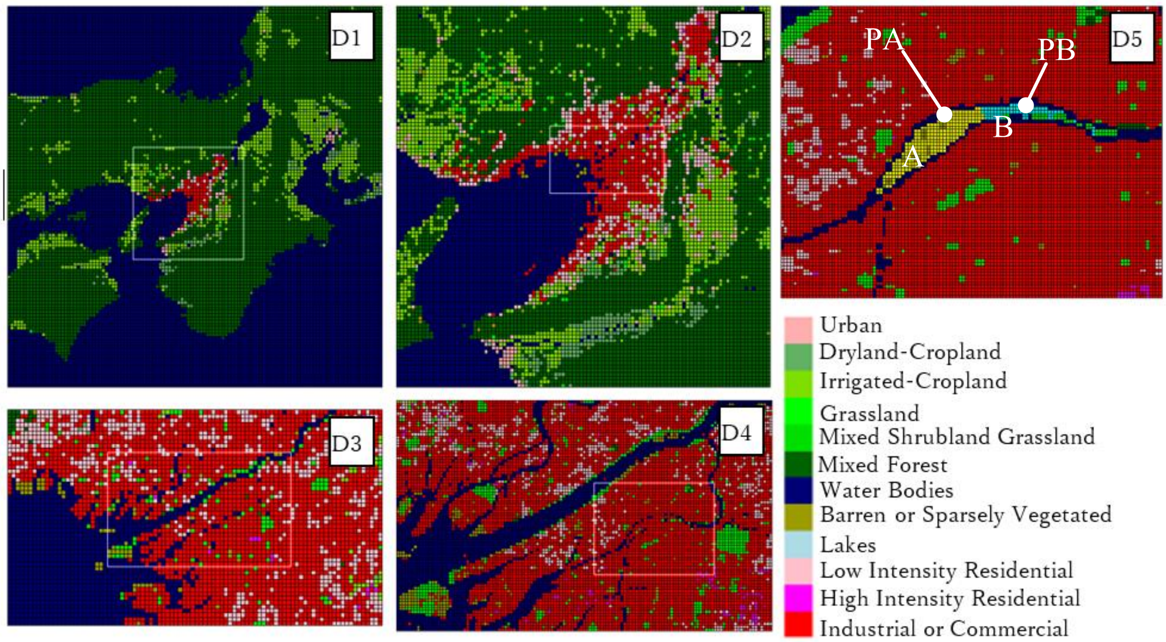

Figure 2: Analysis domain and land use categories. Domains were nested from D1 to D5. The yellow and light blue areas in D5, labeled A and B, respectively, represent Nakanoshima district where the urban parameters were modified for D4 and D5 in the REV case.

August 31, 2010, was selected as the simulation date. On that day, mobile observation of the air temperature was conducted around Nakanoshima district. The initial and boundary conditions for the meteorological elements were obtained from the Final Operational Global Analysis database supplied by the National Centers for Environmental Prediction with 1° resolution and 6-h intervals. The calculations began at 0900 Local Standard Time (LST) on August 29, 2010; the model results obtained from 0000 to 2400 LST on August 31, 2010, were used for the following analyses.

Table 2: Urban parameters

	Urban fraction	Roof level (m)	Building width (m)	Road width (m)	Sky view factor
Low-intensity residential	0.50	5.0	8.3	8.3	0.57
High-intensity residential	0.90	7.5	9.4	9.4	0.48
Industrial/commercial	0.95	10.0	10.0	10.0	0.41
Area A	1.00	36.7	50.0	109.3	0.72
Area B	1.00	28.7	50.0	104.2	0.76

3. Results and Discussion

The surface wind data obtained at the stationary points located near the western and eastern ends of Nakanoshima district indicate that sea breezes (westerly winds) dominated the district almost entirely on the analysis day. Land breezes (easterly winds) were observed only at the eastern endpoint early in the morning, at 0640–0830 LST.

3.1 Model performance

Statistical evaluation of model results was conducted by using the measurements of nine surface monitoring stations (P0–P8 in Fig. 1(a)) operated by Japan Meteorological Agency in Osaka Prefecture. Because the urban parameters used in the REV case reflect actual urban block geometry more accurately than those in the CNTL case, we used REV case results in the model evaluation. The statistics are defined as follows:

Mean bias error (MBE):

$$MBE = \overline{M} - \overline{O} \tag{1}$$

Mean gross error (MGE):

$$MGE = \overline{|M - O|} \tag{2}$$

Root mean square error (RMSE)

$$RMSE = \left\{\overline{|M - O|^2}\right\}^{\frac{1}{2}} \tag{3}$$

Index of agreement (IA)

$$IA = 1 - \frac{\overline{(M-O)^2}}{\overline{(|M-\overline{O}|+|O-\overline{O}|)^2}} \tag{4}$$

where O represents the surface measurements and M represents model values (wind speed at 10 m or air temperature at 2 m) at the monitoring stations. Both data are hourly values. The overline indicates the arithmetic mean of all hours for all points. Table 3 shows the results and the benchmarks recommended by Emery et al. (2001). The MBE and RMSE values of wind speed and the MGE and IA of air temperature were within the recommended ranges. The IA of wind speed and MBE of air temperature were beyond the ranges but were very close to the boundaries. The MBEs indicate that the model tends to overpredict the wind speed and underpredict the air temperature. Figure 3 shows time variations of wind and air temperature at the five stations in closest proximity to the study area. The agreement between the model results and the observations was fairly good. The model results successfully reproduced the time variations in wind and temperature even during in the spin-up period.

Table 3: Evaluation indices of agreement between model and observation results. Boldfaces indicated data within the benchmarks recommended by Emery et al. 2001.

	Wind speed			Air temperature		
Index	MBE (m/s)	RMSE (m/s)	IA	MBE (°C)	MGE (°C)	IA
Benchmarks	≦±0.5	≦2.0	≧0.6	≦±0.5	≦2.0	≧0.8
Model result	**0.44**	**1.63**	0.54	-0.56	**0.87**	**0.96**

3.2 Comparison of air temperature distributions with mobile observation results

For comparison with the model results in Nakanoshima district, we used mobile observation results obtained by Yoshida et al. (2012). Briefly, the observation was conducted on August 31, 2010. We began six observations, at 0900, 1100, 1400, 1600, 1800, and 2000 LST. The observation area (enclosed in the white line in Fig. 1 (b)) was approximately 3.5 km E–W and 1.5 km N–S, and the area was divided into 13 blocks that were observed simultaneously. In each block, geographical position and air temperature data were recorded for 30–40 min at 1-s intervals by traveling on bicycles equipped with a Global Positioning System (GPS) logger (eTrex H, Garmin Co., accuracy <10 m) and a thermometer (RTR-53A thermo-hygrometer or RTR-52A thermometer, T&D Co., thermistor type, accuracy <±0.3°C). The thermo–hygrometer coupled sensor was set in a double-tube shield equipped with a motor fan to facilitate ventilation. In some blocks, theromo-only sensors were used. The theromo-only sensor was also set in the double-tube shield, but it was ventilated naturally (without a fan) because the sensor was small in size. The measurement height was 1 m above ground level. Delay of temperature variation arising from a finite time constant of the thermometer sensors was adjusted by assuming that the response of the sensors could be approximated by a first-order delay system. Because the instantaneous fluctuation of the temperature was large, those values were smoothed with a moving average of 9 s. Data obtained at a traveling speed less of than 5 m/s were excluded to prevent disturbance arising from radiation heating caused by insufficient ventilation. To eliminate the influence of diurnal variation during traveling, the temperature data were converted to values at the start of the observation by referring to the temperature variation of stationary sites around the analysis area. Finally, these point data were interpolated into grid values with the same horizontal resolution as the numerical model (D5) by using an inverse square distance weighted method.

Figure 4 shows the horizontal distribution of air temperature and wind vectors around Nakanoshima district. The distribution of wind vectors and air temperatures in the model results (REV case) were at 10 m and 2 m from the ground surface, respectively. The mobile measurements revealed air temperatures 1 m above the ground. The model obtained temperatures lower than the mobile measurements; however, the maximum and minimum temperatures were comparable. In Nakanoshima district, relatively cooler regions were found through both simulation and observation. Although the building density in the outskirts on the northern side of Nakanoshima district was as low as that in the district, the default urban parameters were assigned. Therefore, low temperatures in the area were not reproduced.

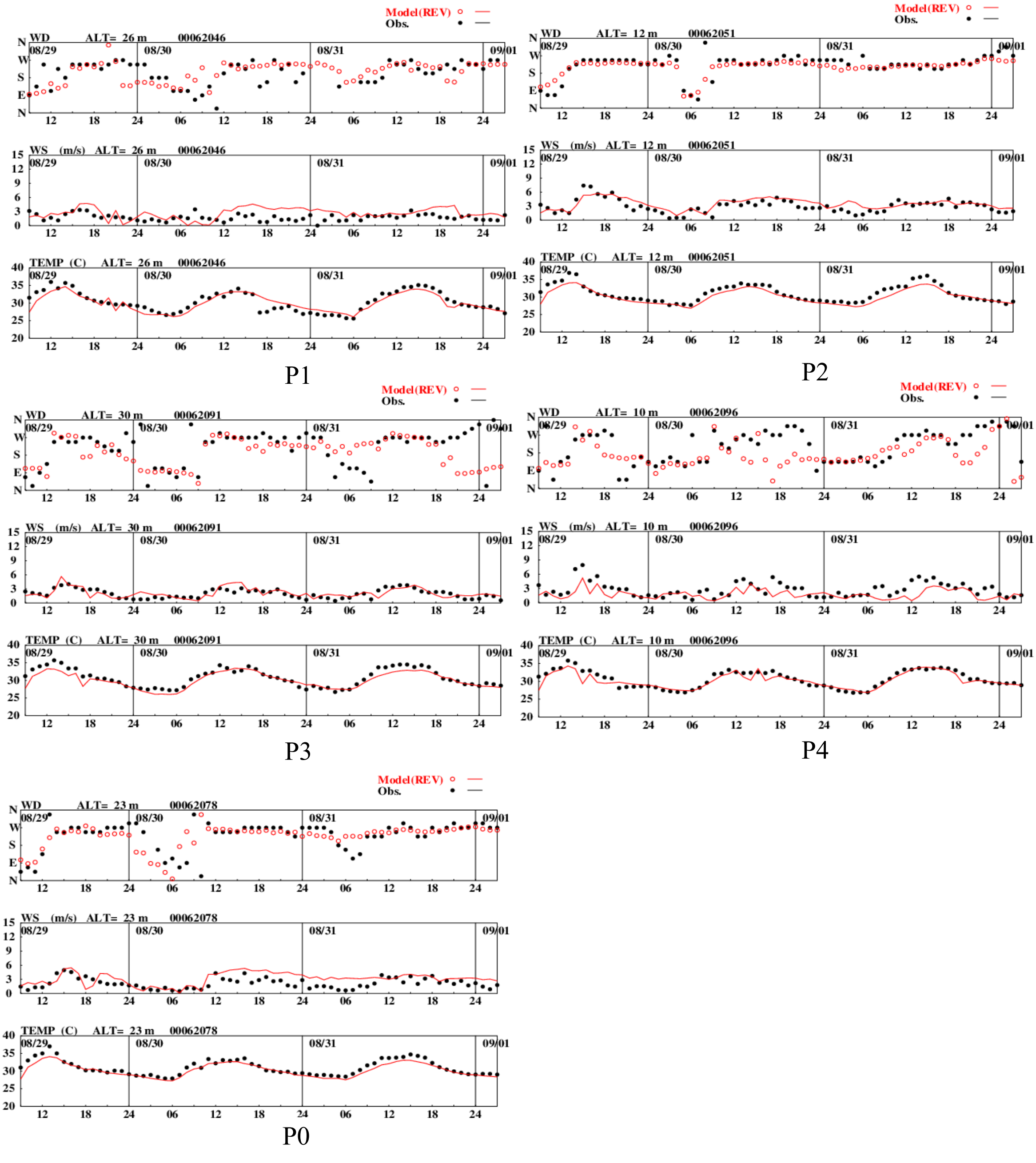

Figure 3: Comparison of model results (REV case) and observed values at surface monitoring stations (P0–P4) in Osaka Prefecture. The observed wind speed was converted to the value at 10 m above ground level using a log law. August 29 and 30 represent the spin-up period. The model result is the grid value of the smallest domain in which the station is included.

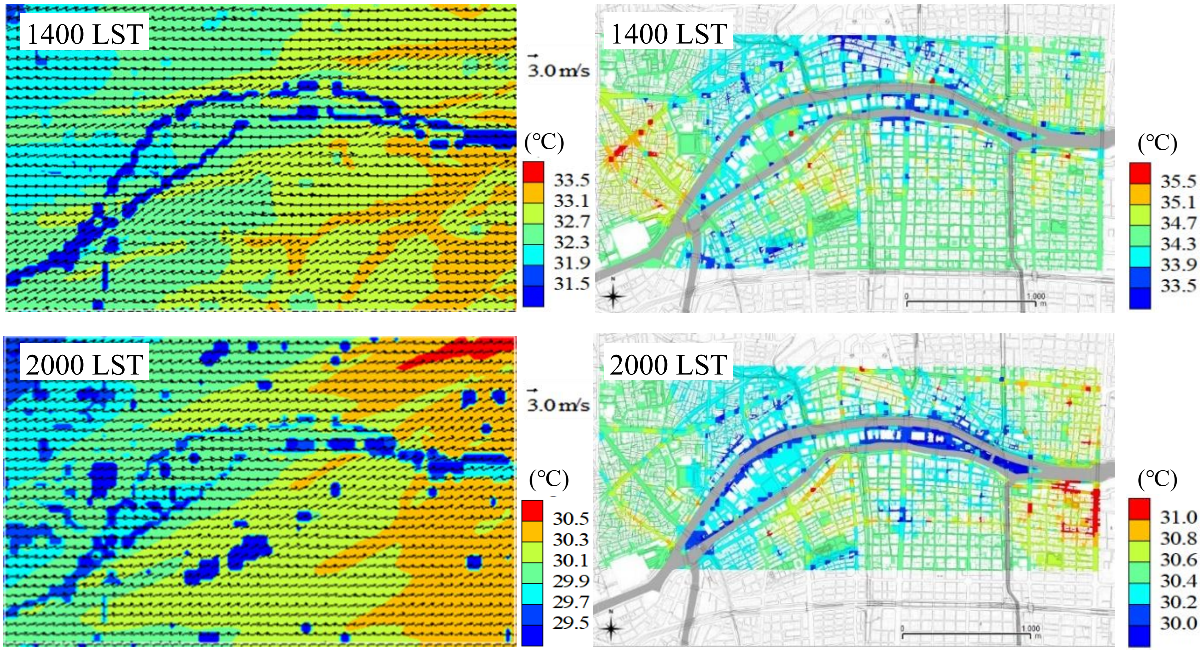

Figure 4: Air temperature distribution on August 31, 2010, in D5. Left column: model results (REV case) with wind vectors. Right column: observation results by mobile measurement.

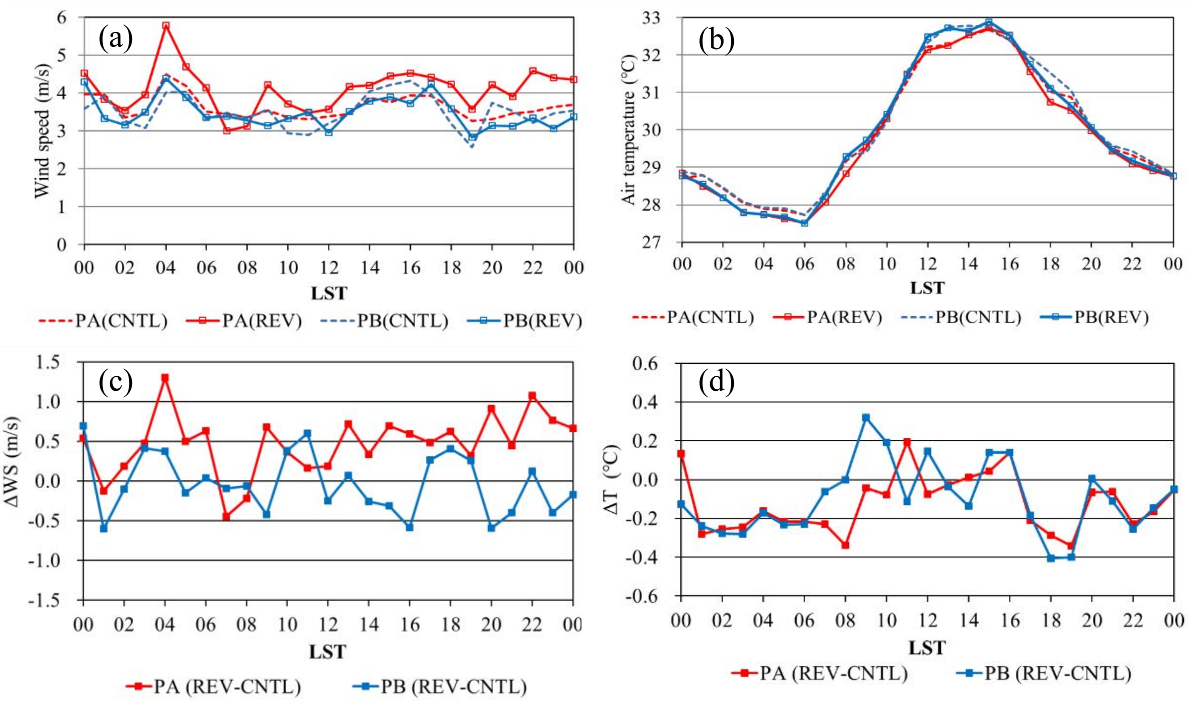

Figure 5: Time variation of (a) wind speed at 10 m and (b) air temperature at 2 m. PA and PB are the sampling points shown in Fig. 2. Solid line with symbols: REV case. Broken line: CNTL case. (c) and (d) show REV-CNTL values in wind speed and air temperature, respectively.

3.3 Effect of building density on wind speed and air temperature

Figure 5 shows the model results of wind speed at 10 m and air temperature at 2 m. PA and PB are the sampling points in the western (Area A) and eastern (Area B) parts of Nakanoshima district, respectively, as given in Fig. 2. Owing to the low building density, the wind speed in Area A is generally approximately 0.5 m/s higher in the REV case than in the CNTL case. This leads to significant ventilation in the area. Figure 6 (a) shows the horizontal distribution of wind speed difference (REV-CNTL), averaged for 6 h based on 10-min interval data. In Area A, it is clear that the wind speed was increased in the entire region owing to the characteristics of urban geometry. On the contrary, the difference in wind speed in the REV and CNTL cases did not show a particular tendency in Area B; however, the road width and roof level values were not significantly different from those in Area A. This result could have been caused by wind blocking owing to the narrow shape of Area B.

Figures 7 (a) and (b) show temperature variations of the ground surface and building wall surfaces, respectively, as estimated by the UCM model. The sky view factors in both Area A and Area B were larger in the REV case than those in the CNTL case. Thus, in the REV case, significant radiation cooling occurred with a decrease in surface temperatures on the ground and building surfaces at nighttime. Therefore, the nighttime air temperatures in the REV case were approximately 0.2 °C lower than those in the CNTL case (Fig. 5 (b), (d)). The lower temperature in the nighttime was distributed uniformly in Nakanoshima district (Fig. 6 (b)). In the daytime, the surface temperature of the ground and building walls in the REV case were higher than those the CNTL case. However, the air temperature in the REV case was not significantly different from that in the CNTL case. Because ratio of the total surface area to the coverage area, (roof+wall+ground)/(roof+ground), and the building coverage ratio, roof/(roof +ground), in the REV case are smaller than those in the CNTL case, the sensible heat flux from the urban canopy layer in the REV case was also slightly smaller than that in the CNTL case even in the daytime (Fig. 7 (c)). The sensible heat from those surfaces was diluted in a mixed layer under unstable conditions in the daytime. Moreover, in Area A, the significant ventilation in the REV case partly suppresses the increase in air temperature. Therefore, the influence of urban block geometry on air temperature is considerably lower than that on the wind.

As shown in Fig. 6 (b), the differences in urban parameters did not influence the temperature at all in the daytime. The differences in air temperature between the results in the REV and CNTL cases were relatively small, at less than 0.4 °C. In this study, however, large differences in air temperature, such as exceeding 1 °C, were not expected to occur basically. In both cases, Nakanoshima district is covered with artificial surfaces such as asphalt and concrete. The difference between these cases lies in the urban parameters only.

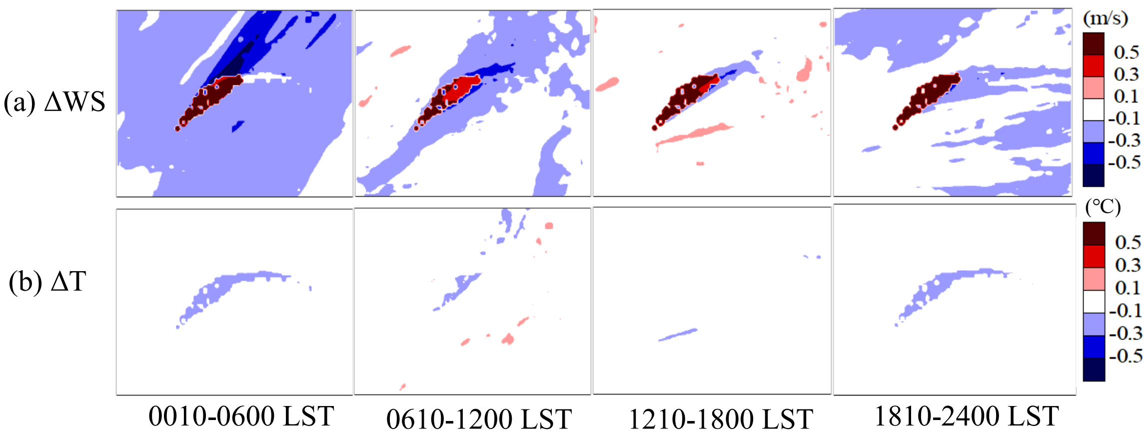

Figure 6: Difference between REV and CNTL cases. The horizontal distribution is shown for REV-CNTL values in the D5 domain. (a) Wind speed at 10 m; (b) air temperature at 2 m.

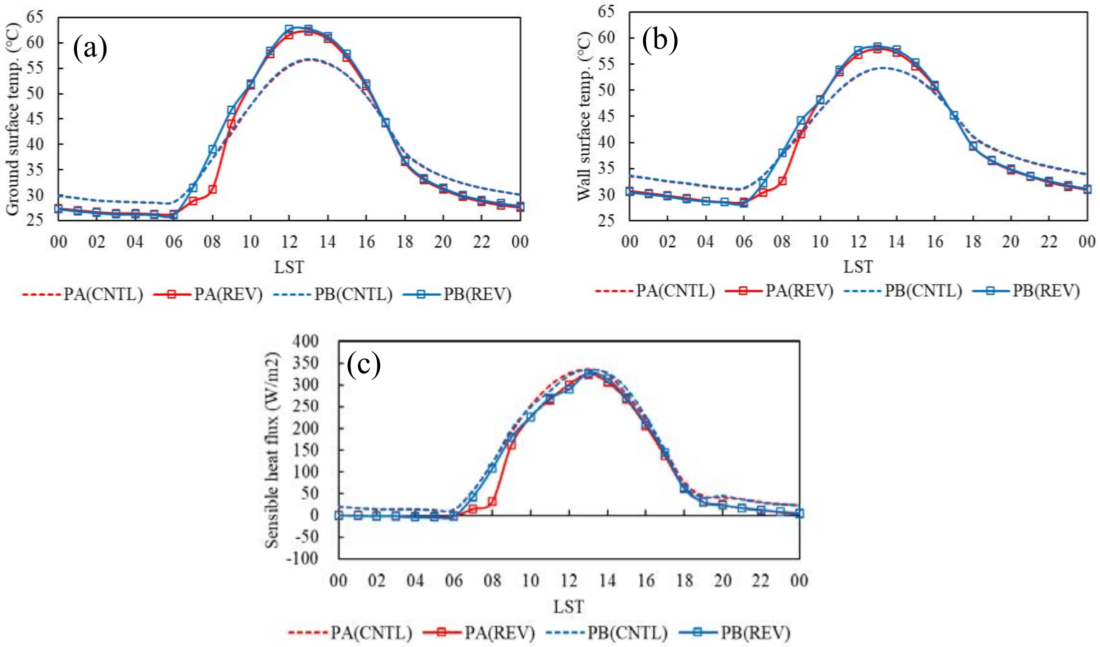

Figure 7: Time variation of (a) ground surface temperature, (b) building wall temperature, and (c) sensible heat flux from the urban canopy layer, at PA and PB. Solid line with symbols: REV case; broken line: CNTL case. In the REV case, a suppression in surface temperature increase owing to cloud shadow occurred at PA during 0700-0900 LST.

3.4 Effect of rivers surrounding Nakanoshima district

Land use patterns in the RF case are shown in Fig. 8. The urban parameters in Nakanoshima district are the same as those in the REV case. The water area at the northwest corner was not changed to land grids because this area is part of a large river and evaluation of its influence is not included in this study. To discuss the influence of existing rivers on the local meteorological field, we examined the differences between the REV and RF results (REV-RF).

Figure 9 (a) shows the horizontal distribution of wind speed difference (ΔWS) averaged for 6 h based on 10-min interval data acquired on August 31, 2010. Large ΔWS owing to the small roughness of the water was observed along the rivers throughout the day. Because the ground properties affect surface flow more directly under stable condition, the magnitude of ΔWS in the nighttime was larger than that in the daytime. However, the high ΔWS over the rivers did not exert a significant effect on the wind speed in Nakanoshima district. The influence of rivers on the ventilation in the district was significantly less than that of the urban block geometries.

Figure 9 (b) shows the horizontal distribution of air temperature difference (ΔT). Similar to the ΔWS, ΔT showed large changes over the river grids, and the rivers acted as cooling sources from the morning to midnight. ΔT was distributed in a broader area, compared with that shown in Fig. 6 (b). Daytime cooling by the rivers was small but was comparable to the change in radiative cooling at night caused by the sparse urban blocks. In Nakanoshima district, ΔT change larger than ±0.1 °C was observed only in the morning, at 0610–1200 LST. The distribution of the influential area depended on the wind direction.

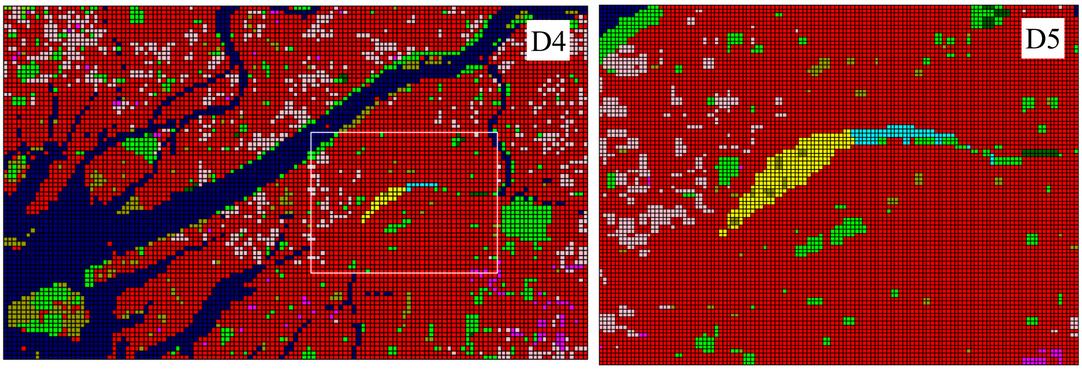

Figure 8: Land use map in the RF case. The category color is the same as thaaat in Fig. 2. Water grids covered by D5 domain, except for the northwest area, were changed to the category "industrial or commercial." The land use categories of other grids are the same as those in the REV case.

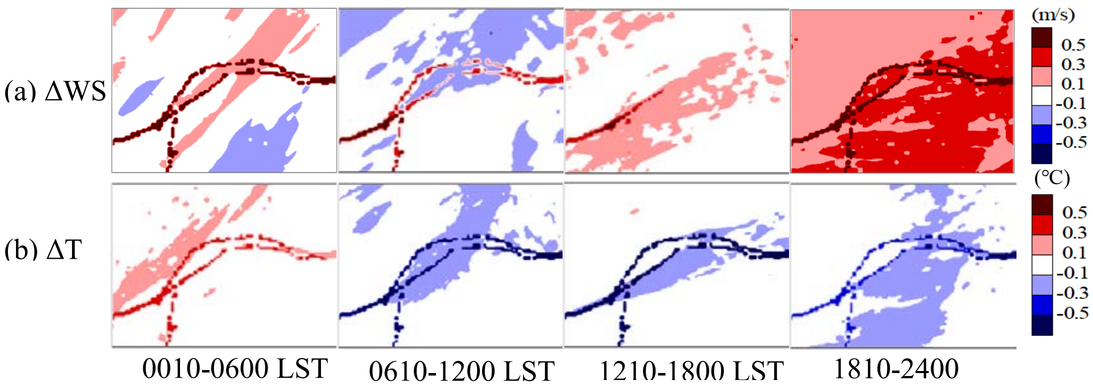

Figure 9: Difference between REV and RF cases. The horizontal distribution of REV-RF values in D5 domain are shown. (a) Wind speed at 10 m; (b) air temperature at 2 m.

4. Conclusion

In the study area, the low building density contributes to significant ventilation in the area. The large sky view factor decreases the air temperature in the nighttime but increases the surface temperatures of the ground and buildings in the daytime. However, the air temperature in the daytime is not significantly influenced because the sensible heat from the urban surfaces is diluted in a mixed layer, with the significant ventilation partly suppressing the air temperature increase. Therefore, the influence of urban block geometry on air temperature is considerably lower than that on the wind. The influence of rivers on the ventilation in Nakanoshima district is significantly less than that of the urban block geometries. The cooling effect of the rivers in the daytime is comparable to the change in radiative cooling caused by the sparse urban blocks.

References

1. C. Emery, E. Tai, G.Yarwood, Enhanced meteorological modeling and performance evaluation for two Texas ozone episodes, *Project report prepared for the Texas Natural Resource Conservation Commission*, Texas Natural Resource Conservation Commission, (2001), 235p.

2. H. Kono, D. Narumi, Y. Shimoda, Osaka, Klimaatlas for Urban Environment, *Architectural Institute of Japan Ed.*, (2000), pp.53-65, Gyousei (in Japanese).
3. T. Kubota, M. Miura, Y. Tominaga, A. Mochida, Wind tunnel tests on the nature of regional wind flow in the 270 m square residential area, using the real model, Effects of arrangement and structural patterns of buildings on the nature of regional wind flow Part 1, *J. Archit. Plann. Environ. Eng., Architectural Institute of Japan,* 529 (2000), pp.109-116 (in Japanese).
4. H. Kusaka, Coupling a single-layer urban canopy model with a simple atmospheric model, Impact on urban heat island simulation for an idealized case, *J. Meteor. Soc. Japan,* 82-1 (2004), pp.67–80.
5. Osaka City, "Kaze-no-Michi" vision [Basic policy], 2011, available from http://www.city.osaka.lg.jp/kankyo/page/0000123906.html, (accessed on 1 April, 2018) (in Japanese).
6. Y. Shimoda, Y. Takahara, S. Kametani, D. Narumi, M. Mizuno, Estimation and Evaluation on Energy Flow in Osaka Prefecture, Material and Energy Metabolism in Urban Area and Their Relationships with Buildings Part 2 (in Japanese), *J. Archit. Plann. Environ. Eng., Architectural Institute of Japan,* 555 (2002), pp.99–106.
7. W.C. Skamarock, et al. A description of the advanced research WRF Ver. 3, *NCAR Technical Note*, National Center for Atmospheric Research, (2008), 113p.
8. H. Takebayashi, M. Moriyama, K. Miyake, Analysis on the relationship between properties of urban block and wind path in the street canyon for the use of the wind as the climate resources, *J. Environ. Eng., Architectural Institute of Japan*, 74 (2009), pp.77-82 (in Japanese), doi:10.3130/aije.74.77.
9. M.S. Wong, J.E. Nichol, P.H. To, J. Wang, A simple method for designation of urban ventilation corridors and its application to urban heat island analysis, *Build. Environ.*, 45 (2010), pp.1880-1889, doi:10.1016/j.buildenv.2010.02.019.
10. A. Yoshida, R. Yasuda, K. Takenaka, S. Kinoshita. Mobile observation of air temperature and humidity distributions in Osaka-Nakanoshima area during summer sea breeze, *8th International Conference on Urban Climates*, (2012), 4p.