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Effects of sea breeze on thermal environment as a measure against Tokyo’s urban heat island

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Abstract

Most megacities in Japan are located in coastal areas where thermal mitigation due to sea breeze in summer can be expected. In Tokyo’s waterfront districts, the urban heat island (UHI) condition has been studied by measuring the air temperature and wind velocity along rivers and streets. In this study, we have carried out a large-scale numerical simulation of the thermal environment of Tokyo’s 23 wards using a supercomputer called the “Earth Simulator,” which enables us to obtain a multiscale condition of the UHI from a building scale to an urban scale, with 5 billion meshes. Consequently, observation and simulation results of air temperature are in good agreement with each other. The numerical results have also revealed an interesting phenomenon, i.e., the formation of an organized structure in an urban boundary layer. In addition, we have investigated the effects of sea breeze on the urban thermal environment by carrying out numerical simulations taking into account urban renewal plans.

Key words: heat island, numerical simulation, Earth Simulator, Tokyo, CFD

1. INTRODUCTION

In recent years, the urban heat island phenomenon has become an important social problem for the Japanese government. Tokyo area is located facing the Tokyo bay, and it is well known that cool sea breezes flow over a wide area during the daytime in summer. Therefore, appropriately introducing cool sea breezes into urban spaces can be considered to be an effective measure for reducing UHI effects. In urban areas, various types of buildings such as residential and office buildings exist in large numbers, and the scale of vortices among these buildings is extremely small as compared to that of UHI circulation. In mesoscale analyses, the abovementioned buildings are generally modeled using a roughness length. Therefore, it has been difficult to evaluate the airflows of both an urban space and an urban boundary layer. In this study, we have developed a numerical simulation tool that can resolve individual buildings on the Earth Simulator for analyzing the UHI. This paper reports the recent simulation results obtained for an entire area of Tokyo's 23 wards.

2. SIMULATION OF TOKYO’S 23 WARDS

2.1 Simulation area

Figure 1 shows the horizontal domain and topography employed in the simulation. The computational domain has a size of 33 km (x, East-West direction) × 33 km (y, South-North direction) × 500 m (vertical direction), which covers the whole area of Tokyo's 23 wards and a part of Tokyo Bay. The domain is divided into 5 m-grids horizontally and 1 m to 10 m intervals vertically. The total number of grid points is over 5×10^9 including buffer areas outside the domain. Using 300 nodes of the Earth Simulator, the total computation time is approximately 16 hours.

2.2 Model and setting

The CFD code is based on the k-ε turbulent model which is widely used in the engineering field. The CFD model is modified with consideration of the potential temperature, Coriolis force, and the buoyancy of vapor.

The simulation has been run for 1400 JST, July 31, 2005. The meteorological initial and boundary conditions, including potential temperature, pressure and wind data, have been set using the output of a mesoscale simulation. A multi-grid

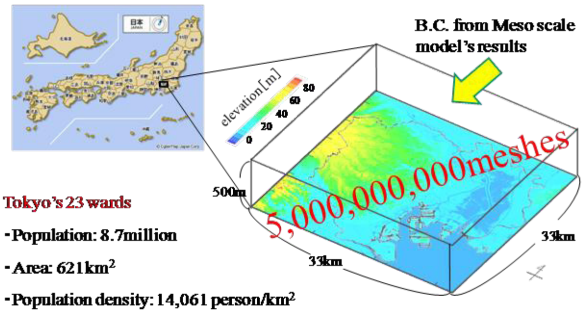


Figure 1. Domain of simulation of Tokyo's 23 wards

approach has been applied to improve the computational efficiency. With a Courant number of 5, the total numbers of iteration steps are 3,000 for the spin up run with 100 m horizontal resolution, 5,500 for the spin up run with 20 m horizontal resolution, and 3,100 for the main run with 5 m horizontal resolution.

2.3 Input data

Input data is shown in Figure 2. Topology has been set up by a five meter mesh resolution from the geographical survey institute. Building location and Land cover such as asphalt, concrete, water have been set up using GIS data of the Tokyo metropolitan government. Building height has been derived from laser measurement data by the geographical survey institute. Anthropogenic heat has been set considering three dimensional release points and the difference between sensible and latent heat.

3. SIMULATION RESULTS

Figure 3 illustrates the air temperature distribution of the Shimbashi district located in Tokyo bay area. Air temperature along each street is displayed in the figure, making it possible to study the urban heat island phenomena on the urban district scales. Air temperatures around JR Shimbashi are extremely high. On the other hand, temperatures around Hama-Rikyu Garden, the Sumida River, and Hibiya Park are low. In addition, the air temperature around the sky scrapers named Sio-Site is low. This is because of the low value of building ratio in this area, which allows sea breezes to enter the gaps between buildings.

Figure 4 shows an example of the simulation results obtained for a riverside area. The river runs meandering through a field, and wind blows along the river. At the left-hand side of the curve shown in the middle, wind goes straight line and cool air enters into the residential area. The same phenomena are observed in the area at the right hand-side of the upstream curve. Thus, the temperature on both sides of the river become lower than that of the inland built-up area. Numerical results showed that the cooling zone extends from approximately 100 m to 200 m.

The horizontal distribution of air temperature at 10 m above the ground achieved by simulation is shown in Figure 5. The prevailing wind direction in this calculation is southerly, which is the typical wind direction at this time period during the summer in Tokyo. The temperature of air increases in the leeward inland, and it is high at Itabashi and in Saitama. On the other hand, the temperature of air is relatively low on the left bottom and right top part of the domain. This distribution trend agrees with the observation results obtained using METROS (Metropolitan Environmental Temperature and Rainfall Observation System, not shown). The temperature of air drops by 1 to 2 ℃above a large green area such as Yoyogi Park and the Imperial

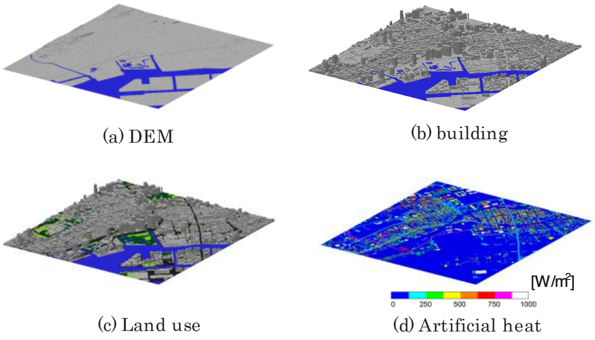

(a) DEM
(b) building
(c) Land use
(d) Artificial heat

Figure 2. Input data for numerical simulation

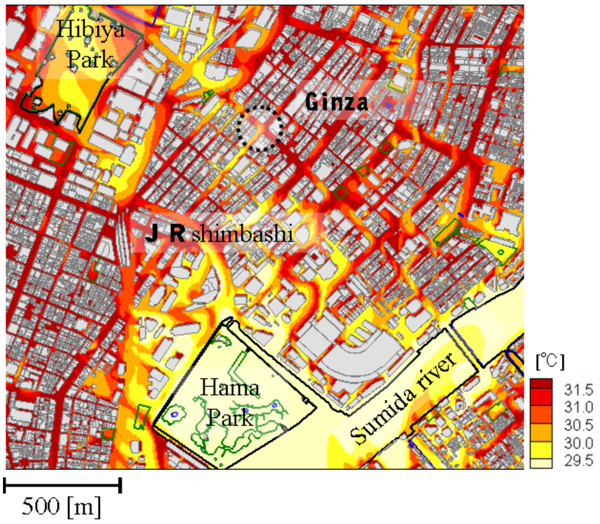


Figure 3. Air temperatures near soil surface
(10m height from ground, 14 o'clock, 31 July, 2005)

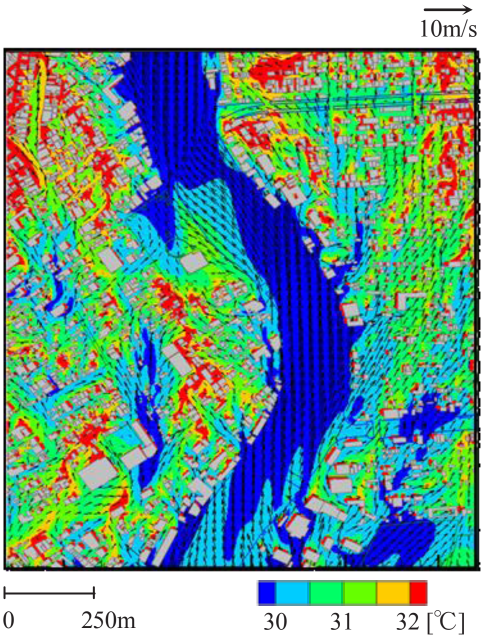


Figure 4. Wind distribution around Sumida River
(10m height from ground, 14 o'clock, 31 July, 2005)

Palace. In addition, it is observed that the higher and lower air temperatures are distributed in a stripe pattern. These stripes can be observed at a pitch of 500 m–2 km, and along the direction of the wind, i.e., in the north-south direction. As wind blows leeward, the thermal stripes meet and become bold.

Although we do not show it here, we have confirmed that the positions of higher and lower air temperatures on the stripe pattern are almost identical to those of upward and downward winds, respectively; the three-dimensional structure of the wind velocity field is similar to the “horizontal roll vortices” in the planetary boundary layer. It is considered that the use of a sufficiently large computational domain in the horizontal directions, together with a sufficiently fine mesh resolution, has enabled us to capture the vortices as clearly as the observational results of the horizontal roll vortices.

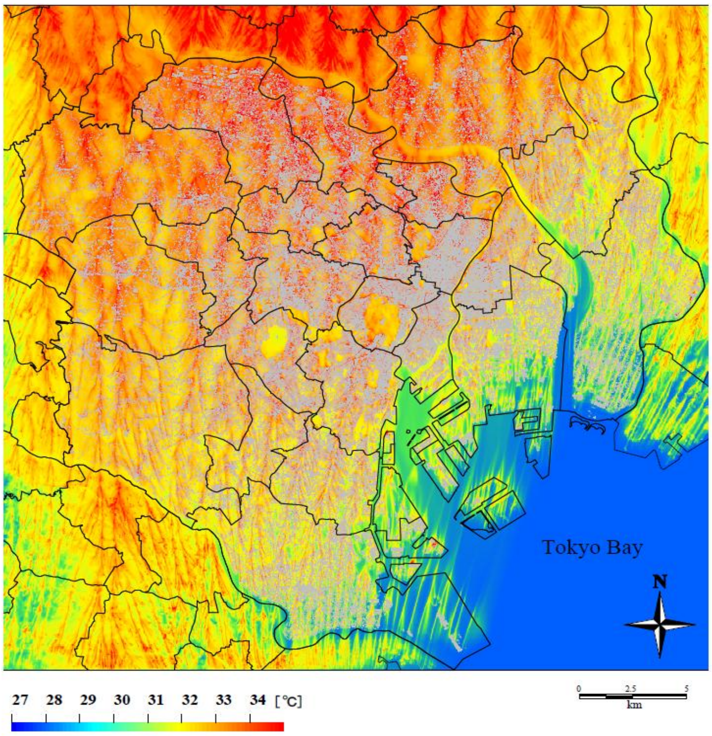


Figure 5. Air temperature of Tokyo’s 23 wards
(10m height from ground, 14 o’clock, 31 July, 2005)

4. SIMULATION OF THEMAL ENVIRONMENTAL CHANGE BY URBAN REDEVELOPMENT IN THE CENTER OF TOKYO

4.1 Case study

A redevelopment plan named the Kanni project is expected to ease traffic jams and lead the urban reconstruction by the Tokyo metropolitan government. From the viewpoint of urban environment, the improvement of thermal environment can be expected by introducing open spaces in the area.

Using the numerical tool as mentioned in the previous section, the authors have carried out a series of simulation studies to assess the impact of urban redevelopment on local ventilation and thermal environment. The computational domain is 2 km (x, East-West direction) × 1.5 km (y, South-North direction) × 0.5 km (vertical direction) with 1 meter horizontal grids. Three cases are conducted in this research.

Case 1: current case, actual land use and building information are used to generate input data;

Case 2: real redevelopment case, the geometrical data has been made based on the Kanni project including main road construction;

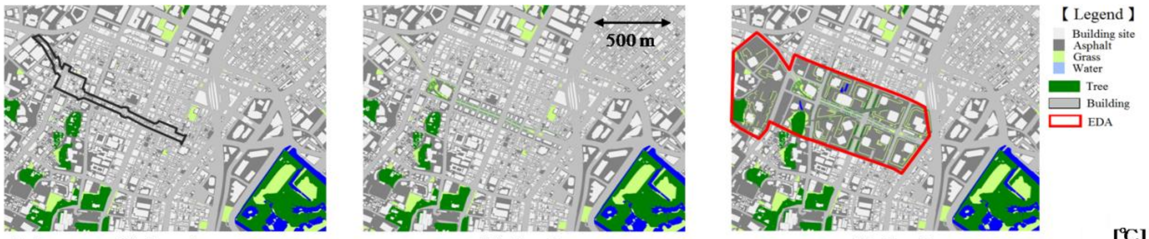
Case 3: virtual redevelopment case, redeveloped area is extended in the Emergency Development Area (EDA) constructing 24 skyscrapers.

4.2 Result

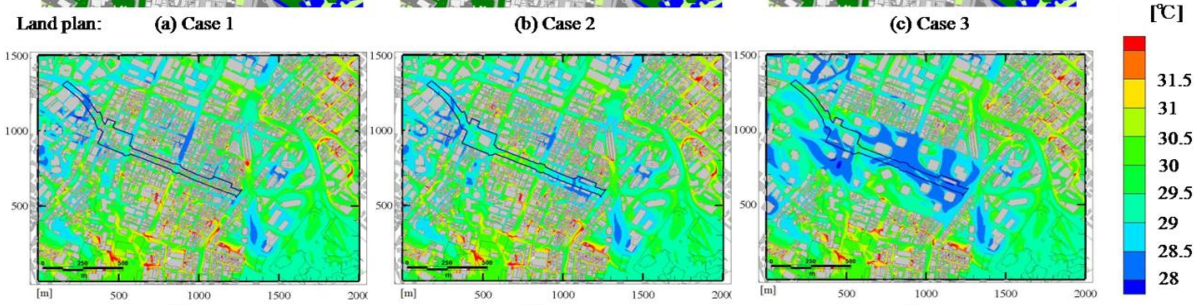
The land use, distribution of air temperature and velocity at 5 m above ground are shown in Figure 6. The black framed area in (a) denotes the zone of the Kanni project and red framed area in (c) the zone of the EDA. The air temperatures in parks and at some wide roads with good ventilations are lower than that in the densely built-up districts. Air temperatures around skyscrapers also show low values due to the shadow effect and strong down-wash caused by building walls. On the other hand, the air temperatures are high in the crowded low-rise blocks. The region of elevated temperatures mostly corresponds to the region where wind stagnation is identified. Comparing the results of case 1 and case 2, the wind velocity increases and temperature drops somewhat along Kanni Road after the redevelopment, whereas the opposite trend is observed at the orthogonally-crossed roads due to the change of wind direction. Another notable point is that, the wind velocity increases above 2 m/s at the parallelly extending road next to Kanni Road. This can be considered as the effect of down-wash caused by the roadside buildings. In case 3, both thermal and ventilation conditions are improved vastly over the whole EDA. In spite of the fact that the gross floor area increased by 17 % compared to the current case, the average air temperature decreases about 1.5 ℃ and the maximum temperature depression is larger than 4 ℃ inside the EDA. The arrangement of skyscrapers is consistently effective in mitigating the local thermal environment. From the fact that increases in air temperature are observed at some place apart from the EDA, especially in the leeward directions, it is considered that the skyscrapers influenced properties of flow current in the upper air.

5. CONCLUSION

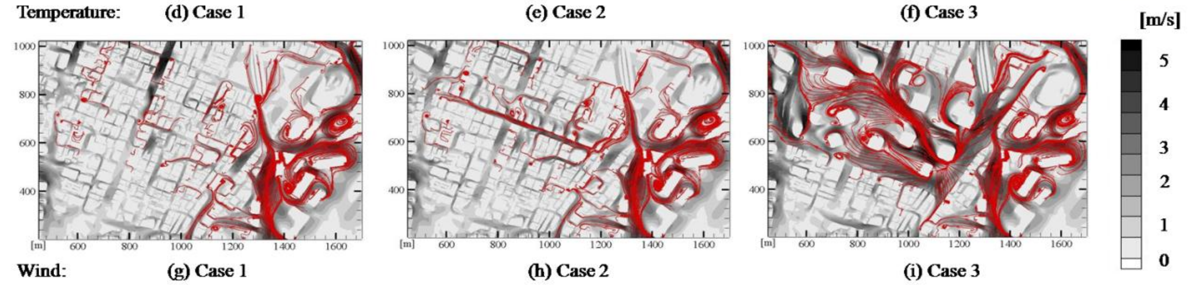
A large scale CFD simulation is performed for the area including the whole Tokyo's 23 wards, and a case study on the actual urban renaissance project is conducted. The numerical result of Tokyo's 23 wards shows the distribution of upward and downward momentum pairs in urban PBL, and suggests that the existence of such vortex pair may contribute to the distributions of temperature and velocity in the lower urban canopy layer. The case study of Kanni Redevelopment Plan has examined the impact of land use and buildings' layout on the urban heat island phenomenon, and pointed out that high-rise and low-coverage urban forms could be effective to improve the thermal and ventilation environment in high-density urban areas.



Land plan: (a) Case 1 (b) Case 2 (c) Case 3



Temperature: (d) Case 1 (e) Case 2 (f) Case 3



Wind: (g) Case 1 (h) Case 2 (i) Case 3

Figure 6. Land use (upper) and air temperature* (middle), velocity *(bottom)
* Numerical simulation result of 5m above soil surface (12 o'clock, 31 July, 2005)

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