

# Large-scale CFD Simulation of Heat Island Phenomenon and Countermeasures in Tokyo

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The urban heat island phenomenon in Tokyo's 23 wards and the impact of Kanni redevelopment on thermal and ventilation environment are analyzed using a thermal environmental analysis system, which can simulate the atmospheric environment with consideration of urban effects such as artificial pavement, building height and anthropogenic heat, etc. The simulation domain for Tokyo's 23 ward extends 33 km × 33km horizontal and includes more than  $5 \times 10^9$  three-dimension meshes. On the other hand, the Kanni simulation targets a 2 km × 1.5 km area around Shimbashi Toranomom District where the construction of highway and huge buildings has been planned. The distribution of air temperature and velocity in Tokyo's 23 wards with very fine resolution is obtained through this research, and the case studies of Kanni redevelopment suggest a possibility of improving local thermal and ventilation environment by urban planning.

**Keywords:** heat island, Tokyo's 23 wards, CFD, heat transport, Kanni redevelopment plan

## 1. Introduction

Several urban renaissance projects have been planned in the Heat Island Countermeasure Promotion Areas which designated by Tokyo Metropolitan Government in April 2005. These areas concentrate the lion's share of economic and political activity in Tokyo, and play a big role in the local climate because of their geographical locations. Assessing the impacts of redevelopment on urban heat islands is one of the most important responsibilities of scientists and government. The authors have developed a new thermal environmental analysis system<sup>1), 2)</sup> which considers various urban characteristics such as the urban surface, building height and anthropogenic heat, etc., to precisely examine the heat island phenomenon. The CFD code is based on the k-ε turbulent model which is widely known in the engineering field. Using this system, authors have analyzed the thermal environment of 5 kilometers squared<sup>1)</sup> and 10 kilometers squared<sup>2)</sup> with their centers at Tokyo Bay waterfront area, on the Earth Simulator, and confirmed that the computational results agree with the observations. This paper reports the recent research results of a 33 kilometers squared simulation that covered the whole area of Tokyo's 23 wards, and a fine-resolution study of the redevelopment project so-called "Kanni Redevelopment Plan".

## 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), covers the whole area of Tokyo's 23 wards and a part of Tokyo Bay. The domain was divided into 5 m-side squares horizontally and 1 m to 10 m intervals vertically. The total number of grid points is over  $5 \times 10^9$  including buffer areas outside the domain. Using 300 nodes of the Earth Simulator, the total computation time is approximately 16 hours.

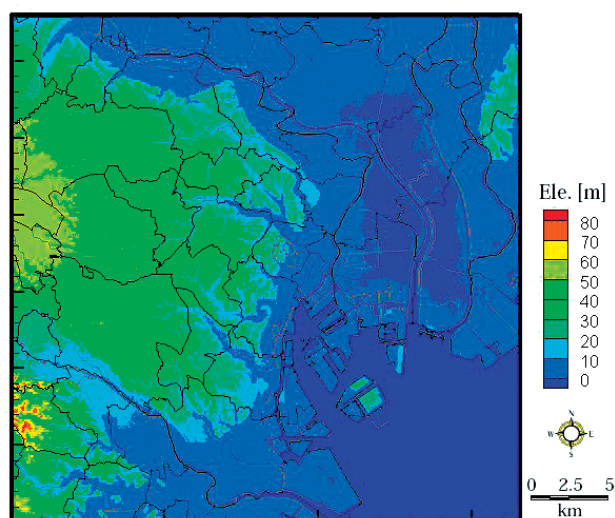


Fig. 1 Domain of simulation of Tokyo's 23 wards.

## 2.2 Model and settings

The characteristics of the simulation code are summarized in Table 1. Unlike other CFD systems, this model is modified with consideration of the potential temperature, Coriolis force, and the buoyancy of vapor. The integrated potential temperature and pressure term was potentially accommodated in the energy transport equation.

The simulation was run for 1400 JST, July 31, 2005. The gridded land surface, building-air ratio, and anthropogenic heat data was arranged according to GIS and the waste heat unit considered the location of sources such as factories, automobiles and buildings. The meteorological initial and boundary conditions, including potential temperature, pressure and wind data, were set using the output of a mesoscale simulation. Here, initial conditions were made by nesting the results of two preceding runs with horizontal resolutions of 100 m and 20 m, successively. With a Courant number of 5, the total numbers of iteration steps were 3 000 for the spinup run with 100 m horizontal resolution, 5 500 for the spinup run with 20 m horizontal resolution, and 3 100 for the main run with 5 m horizontal resolution.

## 2.3. Simulation results

The horizontal distribution of 2 m air temperature by simulation is illustrated in Fig. 2. The prevailing wind direction in this calculation is southerly, which is the typical wind direction at this time period in the summer in Tokyo. The 2 m air temperature increases in the leeward inland, and shows its peak value at Itabashi and in Saitama. On the other hand, the temperature was relatively low on the left bottom and right top part of the domain at the same distance from Tokyo Bay. This distribution trend agrees with the observation results by METROS (Metropolitan Environmental Temperature and Rainfall Observation System, not shown). The 2 m air temperature drops 1 to 2 Celsius degrees above "large green" such as Yoyogi Park and The Imperial Palace (B and A in Fig. 2 respectively), and rivers.

Figure 3 shows the wind speed in vertical direction at 100 m above ground, in which "plus (+)" denotes a flow away from the ground surface (upward) and "minus (-)" denotes a flow toward the ground (downward). The upward and downward wind displays linear patterns with axes approximately in the direction of the prevailing wind, and the intervals grow in the downwind direction. This phenomenon has been commonly known as horizontal roll vortices in the planetary

Table 1 Characteristics of the simulation code.

Item	Description
Flow field	Compressible compound flow under a low Mach number condition
Governing equations	<ul style="list-style-type: none"> <li>• Continuity equation</li> <li>• Momentum equations (Effects of buoyancy, Coriolis force, and drag forces of plants are taken into account.)</li> <li>• Energy equation (Formulated using potential temperature. Release of sensible heat from artificial sources, walls, etc. is taken into account.)</li> <li>• Transport equation for water vapor (Formulated using specific humidity. Release of latent heat from artificial sources, wall, etc. is taken into account.)</li> <li>• Transport equation for turbulent kinetic energy, <math>k</math> (Production of turbulent energy by buoyancy, humidity, and plants is taken into account.)</li> <li>• Transport equation for dissipation rate of <math>k</math>, <math>\epsilon</math> (Dissipation of turbulent kinetic energy by buoyancy, humidity, and plants is taken into account.)</li> </ul> <p>**All equations are formulated based on FAVOR method in order to take into account the effects of the sub-grid scale parts of the ground and buildings.</p>
Turbulence model	Standard $k$ - $\epsilon$ model
Coordinate system	3-dimensional Cartesian coordinate system
Computational grid	Staggered grid
Discretization method	Finite difference method
Spatial discretization	1st order upwind differencing scheme (For convection term.), 2nd order central differencing scheme (Except for convection term.)
Time discretization	Backward Euler method
Algorithm	SIMPLEC method
Matrix solver	AMG-CG method, Bi-CGSTAB method

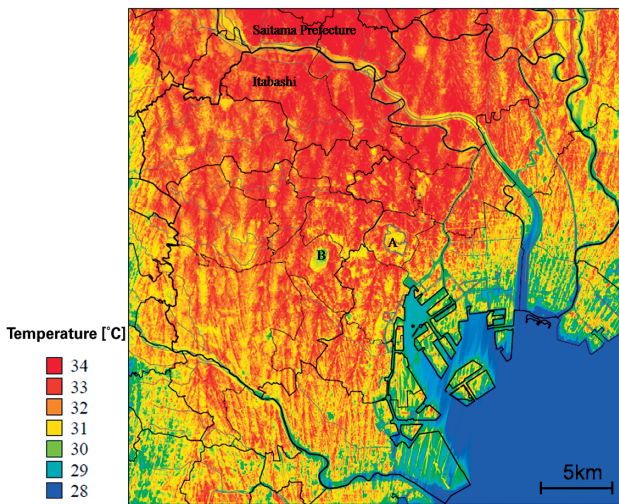


Fig. 2 Simulation result of 2 m air temperature (Tokyo's 23 wards).

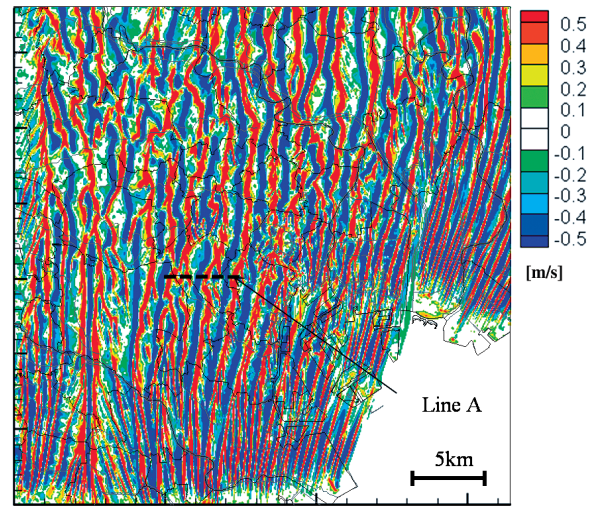


Fig. 3 Vertical velocity at 100 m above ground (Tokyo's 23 wards).

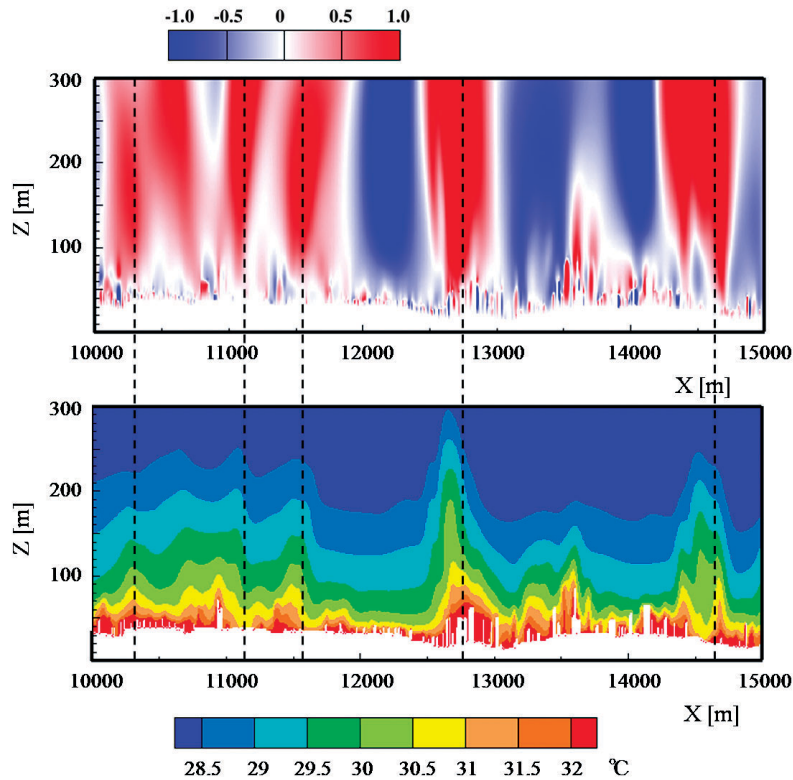


Fig. 4 Temperature and vertical wind speed at Line A in Fig. 3.

boundary layer. The evidence on horizontal roll vortices has been provided by numerous satellite pictures, Radar and Lidar observations, etc., and it is known that a vortex pair may have a lateral dimension of from 500 m to dozens of kilometers<sup>3)</sup>. In general, mesoscale models, whose resolutions are more than 500 m mostly, are used to simulate areas with a scale similar to this research. However the horizontal roll vortices that occurred in the urban PBL have not been reproduced yet. On the other hand, in recent years, attempts have been made by using so-called "Large Eddy Simulation" (LES) models to simulate the development of roll vortices. Three-dimensional LES simulations have indicated that con-

vective instability takes the form of roll-like eddies in the PBL, but they could not yet reconstruct the permanent features of horizontal rolls as clearly as the results from observations because of the limited horizontal extent of the model domain. Figure 4 links the temperature difference with the variation of vertical velocity at "line A" marked in Fig. 3. It is clearly that the position where upward momentum appeared is often accompanied by a high air temperature. The lateral dimension of a vortex pair is from several 10 m to 2 km. Since this model did not simulate the time evolution of momentum, heat and moisture, more researches need to be undertaken to clarify this phenomenon in the urban PBL.



### 3. Simulation of Kanni Redevelopment Plan

#### 3.1 General information

The goal of Kanni Redevelopment Plan is to ease traffic jams and lead urban restructuring in the center of Tokyo. At the same time, the improvement of ventilation and thermal environment in the plan area is expected through the redevelopment. Using the same model as introduced in the previous section, authors have carried out a series of simulation studies to assess the impact of urban renaissance on local ventilation and thermal environment. The horizontal domain is 2 km (x, East-West direction) × 1.5 km (y, South-North direction) with a resolution of 1 meter squared. The vertical domain and the method for boundary and initial conditions set-up are the same as the simulation of Tokyo's 23 wards.

Three cases are conducted in this research.

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

Case 2: redevelopment case, the geometrical data was made based on Kanni Redevelopment Plan;

Case 3: superhigh-rise case, buildings inside the so-called "Emergency Development Area" were arranged by 24 business use skyscrapers, the height of skyscrapers is 200 m (50 floors assumed);

#### 3.2 Simulation results

The land use and distribution of air temperature and velocity at 5 m above ground of 3 cases are shown in Fig. 5. The black framed area in (a) and red framed area in (c) denote the zones of Kanni Redevelopment Plan and Emergency Development Area (EDA), respectively, while the red lines in (g) to (i) illustrate the streamlines.

The air temperatures in parks and at some wide roads with good ventilations are lower than that in the built-up districts. It proves that open spaces may provide cool spots under certain conditions. Air temperatures behind skyscrapers also show low values due to the shadow effect and strong down-wash caused by buildings. 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.

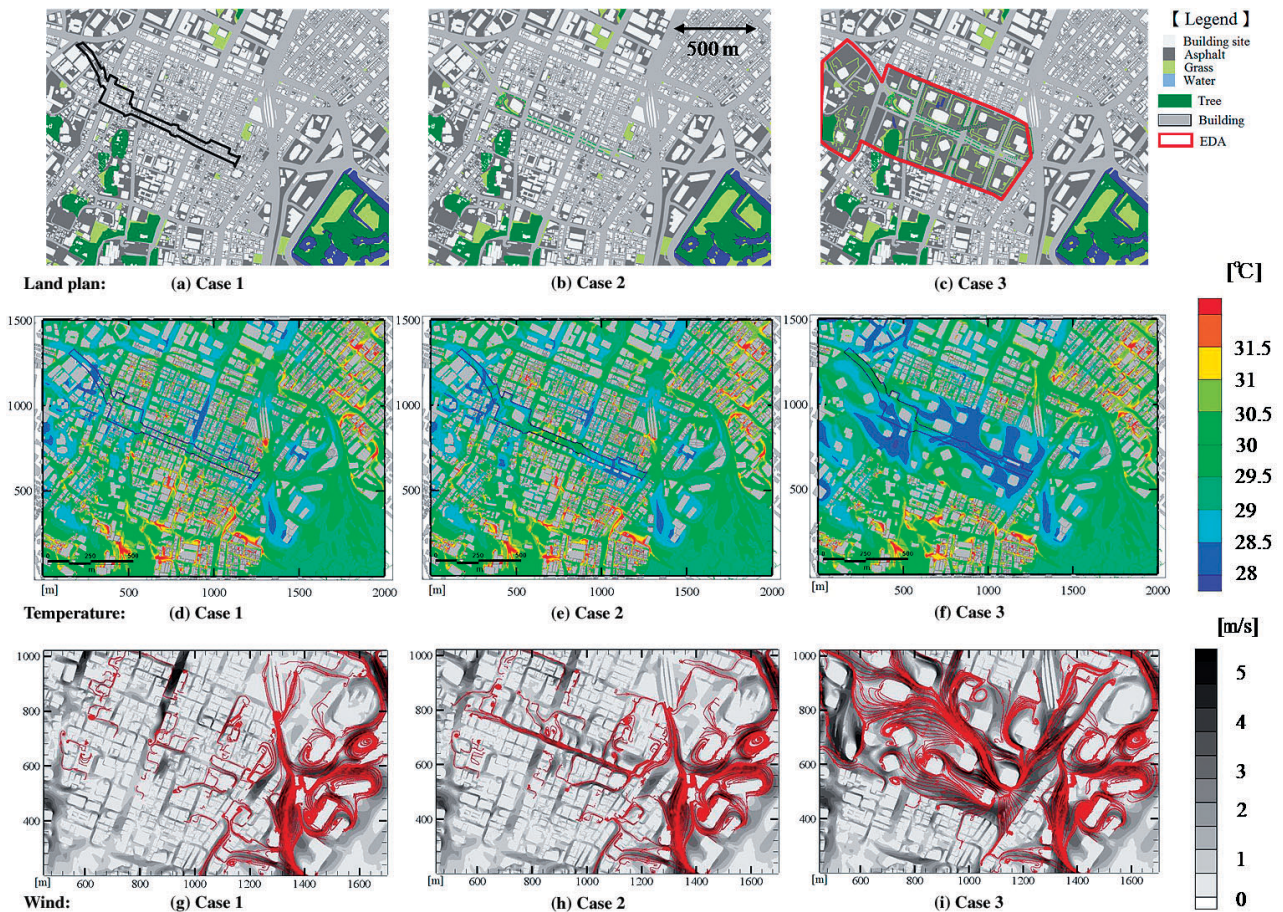


Fig. 5 Land use (upper) and results (temperature: middle, streamline: bottom) of Kanni simulation.

In case 3, both thermal and ventilation conditions are improved vastly over the whole Emergency Development Area. 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 °C and the maximum temperature depression is larger than 4 °C inside the Emergency Development Area. Suitable arrangement of skyscrapers is consistently effective in mitigating the local thermal environment, but its influence is limited on the area where building coverage is lowered. In the fact, somewhat temperature increases are observed at some place apart from Emergency Development Area, especially in the leeward directions, it is considered that the skyscrapers influenced properties of flow current in the upper air.

#### 4. Summary

A large scale CFD simulation is run 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 might contribute to the distributions of temperature and velocity in the lower urban

canopy layer. The case study of Kanni Redevelopment Plan 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.

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# 東京におけるヒートアイランド現象とその対策に関する 大規模CFD解析

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筆者らは、都市のヒートアイランド現象を詳細に検討するため、土地被覆、建物高さ、人工排熱等の都市的効果を分析可能な数値解析システムを地球シミュレータ上に構築し、これまで5km四方、10km四方の解析領域を設定して数値シミュレーションを実施してきた。今年度は解析領域を33km四方に拡張して東京23区全域をカバーする数値シミュレーションを実施した。計算結果より、南風が卓越する場合東京23区の北方から埼玉にかけて高温域が形成される様子が再現されており、東京23区全域のヒートアイランドの状況を明らかに示すことが出来たと考えられる。また、環状2号線地域を対象にした都市再開発ケーススタディーの実施事例を紹介し、今回開発した計算システムが都市再開発計画に伴う熱環境影響の評価に適用できることを示した。

キーワード: ヒートアイランド, 東京23区, CFD, 熱輸送, 環二開発