Development of Numerical Simulation Model of Urban Heat Island

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In order to analyze the urban heat island phenomena, we have developed a numerical simulation tool, which can directly resolve urban structures, on the Earth Simulator. Using this tool, the distribution of airflow and temperature in a 5 kilometers square area in Tokyo was analyzed to evaluate wind passage in the street canyon and cool spot of open space, from the viewpoint of urban planning. To grasp each building effect, horizontal mesh resolution was set at 5 meters. The result showed a good agreement with field measurements, that is, the airflow impacts were weakened and temperature became higher in the densely built-up areas.

Keywords: urban heat island, CFD, airflow, temperature, urban area

1. Introduction

Urban districts of Tokyo are located facing the Tokyo bay, and it is known that sea breezes flow into the whole area during summer days. Some people call the continuous open spaces such as the Arakawa-river, the "Kaze no Miti". In recent years the urban heat island countermeasures became an important theme for political reasons, thus the necessity of the quantitative and qualitative evaluation of environmental resources which exist in urban areas, like parks, rivers, etc. has been pointed out.

On the other hand, in urban areas various types of buildings such as residences, offices, etc. exist in vast numbers, and the structure of their arrangement is extremely minute and complicated compared to that of rivers. Therefore, in Meso-scale analyses, those buildings were generally modeled as roughness parameter. However, it is impossible to evaluate the airflow in the urban space using above mentioned description of buildings.

In this project, we have developed a numerical simulation tool which can resolve individual buildings, on the Earth Simulator, toward analysis of the urban heat island. As a first step, we applied this simulation tool to the analysis of the distribution of airflow and temperature in a 5 kilometers square area in Tokyo district using 5 m mesh resolution.

2. Numerical simulation model

The governing equation is based on the k-ε quadratic equation model in Fig. 1. In order to handle anthropogenic

[Continuous equation]

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_j}\left(\rho u_j\right) = 0$$

[Transport equation for momentum]

$$\frac{\partial}{\partial t}\left(\rho u_i\right) + \frac{\partial}{\partial x_j}\left(\rho u_i u_j\right) = -\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j}\left[\left(\mu + \mu_1\right)\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right)\right] + \rho g_i$$

[Transport equation for heat]

$$\rho C_p\left(\frac{\partial T}{\partial t} + u_j\frac{\partial T}{\partial x_j}\right) = \frac{\partial}{\partial x_j}\left(\left(\lambda + \lambda_1\right)\frac{\partial T}{\partial x_j}\right)$$

[Ideal gas law]

$$P_0 = \rho R T$$

[Transport equation for k]

$$\frac{\partial}{\partial t}\left(\rho k\right) + \frac{\partial}{\partial x_j}\left(\rho k u_j\right) = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_1}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right] + P_k + G_k - \rho\varepsilon$$

[Transport equation for ε]

$$\frac{\partial}{\partial t}\left(\rho \varepsilon\right) + \frac{\partial}{\partial x_j}\left(\rho \varepsilon u_j\right) = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_1}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial x_j}\right] + \frac{\varepsilon}{k}\left(C_{\varepsilon 1}P_k + C_{\varepsilon 3}\max[0, G_k] - C_{\varepsilon 2}\rho\varepsilon\right)$$

here,

$$\mu_1 = \rho C_\mu \frac{k^2}{\varepsilon}, \quad \lambda_1 = \frac{C_p \mu_1}{P_{rt}}$$

$$P_k = \left[\mu_1\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right) - \frac{2}{3}\rho k \delta_{ij}\right]\frac{\partial u_i}{\partial x_j}$$

$$G_k = \frac{\mu_1}{P_{rt}}\frac{g_i}{T}\frac{\partial T}{\partial x_i}$$

x_i :Rectangular Cartesian coordinates, u_i :Wind velocity in x_i direction, t :Time, p :Pressure function, g_i :Component of gravitational acceleration in x_i direction, ρ :Air density, T :Air temperature, C_p :Specific heat at constant pressure, P_0 :Thermodynamic pressure, k :Turbulent kinetic energy, ε :Dissipation rate of turbulent kinetic energy, μ :Molecular viscosity coefficient, μ_1 :Turbulent viscosity coefficient, λ :Thermal conductivity coefficient, λ_1 :Turbulent thermal conductivity coefficient, P_{rt} : Turbulent Prandtl number

$C_\mu = 0.09, \sigma_k = 1.4, \sigma_\varepsilon = 1.3, C_{\varepsilon 1} = 1.44, C_{\varepsilon 2} = 1.9, C_{\varepsilon 3} = 1.45$

Fig. 1 Governing equations

heat release from boilers, the equations for the compressible flow (low Mach number approximation) were applied.

3. Target area for analyses

Map of the target area for this study is shown in Fig. 2. It is the area, whose size is 5 kilometers square, near the mouth of Arakawa-river in Tokyo. The Arakawa-river runs from the north to the south in the study area, and urban area extended on both sides of the river. In the figure, a square frame is shown to indicate the sample area (500 meters square) for intensive study.

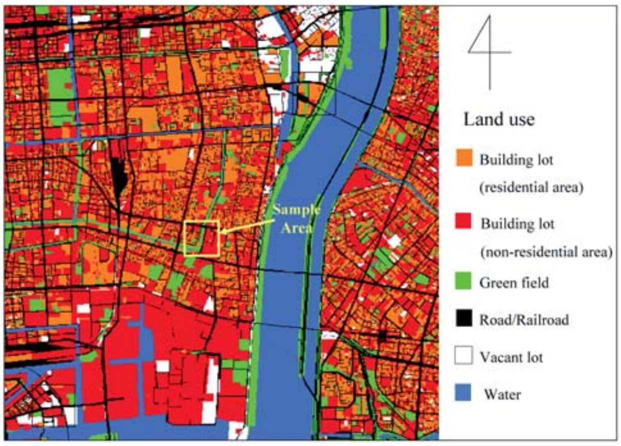

Fig. 2 Land use of Target area (5 km × 5 km)

4. Method of analyses

4.1. Computational domain and grid system

Beside the analyses area mentioned above, buffer-zones (smooth 500 m width floors respectively) were set on both sides of the actual target area. The orthogonal grid was applied to evaluate the urban terrain and topology explicitly.

- Calculation area: 6 km (x: east to west) × 6 km (y: north to south) × 500 m (z: vertical)
- Number of grids: 1,200 (x) × 1,200 (y) × 100 (z)
- Width of the mesh: regular intervals at 5 m (horizontal), irregular intervals from 1 m to 10 m (vertical)

Using the point-sampling method on the GIS data of Tokyo, the data of the locations and the number of stories of buildings was extracted. Story height was set at 3.5 m. Building shapes and soil surface undulation were approximated as stepwise according to the grid lines.

4.2. Boundary conditions

The generalized logarithmic low was applied as boundary conditions of wind on the surface of earth and building's walls. The boundary conditions of temperature on those surfaces are determined by the data which was obtained from the calculation of sub-model considering thermal properties of land use (M. Oguro et al., 2002). Here, land use was estimated from the GIS data of Tokyo.

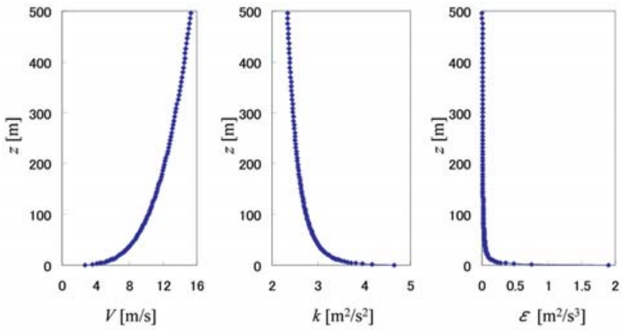

Fig. 3 Vertical profile of the stream-wise velocity V, the turbulent kinetic energy k, the dissipation rate of turbulent kinetic energy ε, at the inlet boundary

Other boundary conditions were set as follows;

- Inlet boundary: As for the velocity of winds, south wind was assumed, and 1/4 power law was applied for the vertical profile of stream-wise velocity (Fig. 3). Standard velocity of wind was set using the observation data in Haneda Airport (summer in 1998). The profile of k and ε are set by using local equilibrium theory.

As for the temperature, a constant value of 28.8°C was set.

- Boundary in the spanwise direction: Symmetry condition
- Outlet boundary: Neumann condition
- Upper boundary condition: Symmetry Condition

4.3. Outline of vector parallelization processing

- Vector operation ratio: 99.50%
- Effective performance against the maximum performance: 12.26%
- Division number: 2(x) × 8(y) × 10(z) = 16 divisions
- Number of nodes used: 20 (160 processors)

5. Discussion

5.1. Results of the whole target area

The horizontal distribution of wind vectors, scalar wind velocity and temperature at the height of 9.7 m are shown in Fig. 4. As for the wind vector distribution, results are plotted at 100 m intervals. Low-rise buildings (those less than 2 stories) are not observed at this measured height, but due to considerable numbers of middle and high-rise buildings in the area, a complicated wind velocity field is formed. In the vicinity of the coast line, until about 2 km inland, the temperature is extremely low due to the cooling effect of sea breeze. Furthermore, along the Arakawa river, distribution of strong winds which coincide with the direction of prevailing winds is observed, and temperatures are lower in these locations. Strong winds and low temperature are also observed in open spaces such as streets, channels and vacant lands. Meanwhile in high density area of buildings, winds are weak and temperatures are high in general.

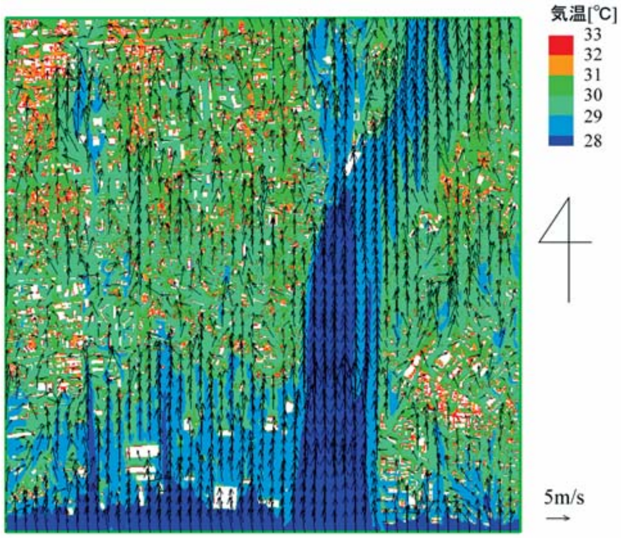

Fig. 4 Horizontal distribution of temperature and wind vectors at the height of 9.7 m in the whole target area

Above mentioned evaluation has been impossible by generally used meso-scale models.

5.2. Results of the sample area

The horizontal distribution of airflow and temperature at the height of 2.5 m in the sample area, whose size is 500 meters square, is shown in Fig. 5. At this scale, the shape and arrangement of individual buildings affect the formation of the field of wind and temperature. In the north-south main street which is located on the left side of Fig. 5, very strong wind field with the same direction of the upper air is formed, and temperature is relatively low. In large open spaces among buildings, although the wind direction is complicated, the wind speed is large and temperature is relatively low. On the other hand, in the densely built-up low-rise building complex displayed on the right side of Fig. 5, the wind speed becomes very small, and the temperature rises greatly.

The simultaneous air temperature observation (M. Moriyama et al., 2002) of different types of urban districts in the summer day showed that the temperatures in the densely

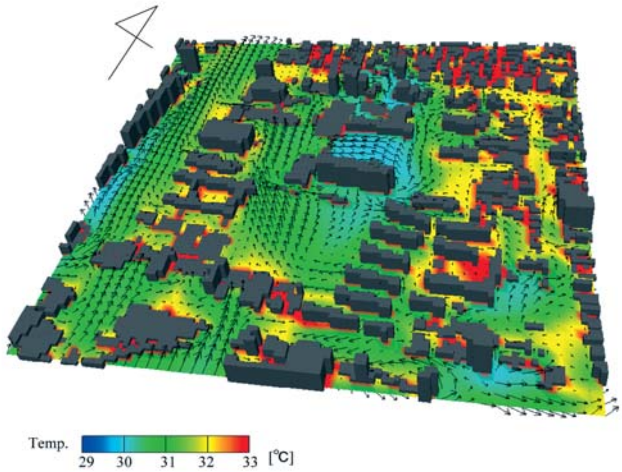

Fig. 5 Horizontal distribution of temperature and wind vectors at the height of 2.5 m in the sample area

built up residential areas were higher than those in the other areas. This tendency accords well with our simulation results.

6. Summary

In this study we analyzed the distribution of temperature and airflow in a 5 kilometers square area in Tokyo by the numerical simulation system, resolving the urban terrain and topology explicitly. As a result, the tendency of the distribution of temperature and airflow was reasonable compared to that of previously conducted observation. In this project, we are planning to analyze the thermal environment in the whole area of 23 wards in Tokyo.

References

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ヒートアイランドの数値モデルの開発

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都市のヒートアイランド解析に向けて、都市構造物を陽に解像可能な数値シミュレーションツールを地球シミュレータ上に構築した。従来のメソスケール解析では、都市に存在する多数の建物を地表面と共に粗度として一括して取り扱うが、本研究では建物壁や屋根面、地表面の起伏を別個に取り扱い、これらの表面からの放熱を考慮して詳細な気温･風の場を都市スケールで解析する。東京に実在する5 km四方の市街地を計算対象として5 mメッシュの水平解像度でCFD解析を実施した。その結果、海風の冷却により、沿岸の2 km域が2°C以上低温化することや、河川では風が強く周辺の建物域に比べて気温の低下が著しいことが分かった。さらに、街路の熱環境を詳細に調べると、建物の密集域では弱風となり気温が高くなること等、既往の実測値との対応も良好であることを確認した。今後はこの解析ツールを東京23区全域に拡張し、都市の風の道の実態を解明する予定である。

キーワード: 都市ヒートアイランド，CFD，気流，気温，都市域