Numerical Simulation of Urban Thermal Environment in the Waterfront Area of Tokyo

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In recent years, countermeasures for the urban heat island have become an important theme for political reasons. It has become urgent to evaluate the effects of environmental resources (such as parks and rivers) in urban areas, qualitatively and quantitatively. Therefore, we have developed a thermal environmental analysis system on the Earth simulator, incorporating various urban effects. In this paper, we report the simulation of thermal environment in the 5 km × 5 km area of the Tokyo seaside, with 5m horizontal mesh resolution.

Keywords: urban heat island, CFD, airflow, temperature, urban area, high building cluster

1. Introduction

Many 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, countermeasures for the urban heat island have become an important theme for political reasons, thus it is necessary to qualitatively and quantitatively evaluate the environmental resources which exist in urban areas, such as parks, rivers, roads.

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 complicated compared to those of rivers. Therefore, in mesoscale analyses, those buildings were generally modeled using roughness parameter. However, it is impossible to evaluate the airflow in the urban space using this description of buildings.

In this project, we have developed a numerical simulation tool which can resolve individual buildings for the analysis of the urban heat island. This academic year, we incorporated the FAVOR method and a plant canopy model to improve the simulation of the urban environment. In addition, we revised the fundamental equations which calculate potential temperature. For future larger scale simulations, in order to increase computational efficiency, we enhanced the vectorization and parallelization of the code, especially in those sections involving matrix solving.

In this paper, we report the simulation of the thermal environment in the 5 km × 5 km area of the Tokyo seaside, where many high rise buildings have been constructed recently requiring an evaluation of the effects of those buildings on the thermal environment.

2. Numerical simulation model

In order to precisely analyze urban heat island phenomena, it is necessary to take into account macro-scale climate characteristics, roughness of ground surfaces, the arrangement and shape of buildings, temperature of urban surfaces, effects of land use and anthropogenic heat by urban activities. Figure 1 shows how these factors are related in the newly developed analysis system.

To create land use and building shape databases, Tokyo metropolitan GIS (Geographic Information System) data

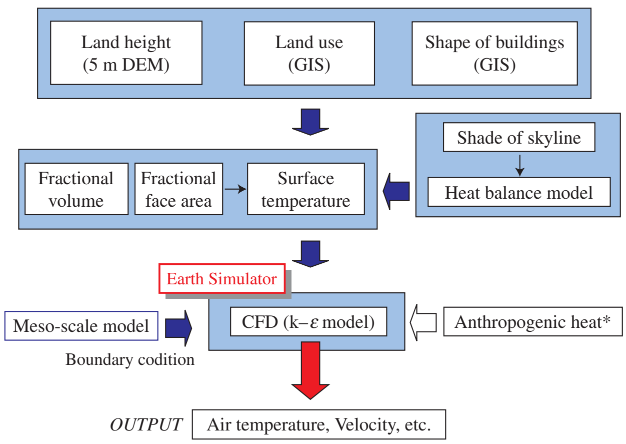

Fig. 1 Diagram of urban heat island analysis.
*In the present study, anthropogenic heat is not considered.

were used with a horizontal mesh resolution of 5 m, which is small enough to resolve individual buildings and most roads in urban areas. In order to take into account the volume of buildings that cannot be resolved with 5 m mesh, a database was constructed of effective volume ratio and open area ratio at each mesh point. For the creation of the land height database, 5 m DEM (Digital Elevation Model) from the Geographical Survey Institute were used.

The temperature of urban surfaces in each computational mesh was set based on the land use and the ratio of shade area, which was calculated 3-dimensinally considering the skyline. The surface temperatures were calculated using a heat balance model, which was run in advance.

In order to take into account the macro-scale climate characteristics, database of boundary conditions for the computational domain was constructed by performing a mesoscale meteorological simulation.

Using the above databases, CFD (Computational Fluid Dynamics) simulation was performed on the Earth Simulator.

3. Model description

The governing equations are based on the compressible Navier-Stokes equation and transfer equation of potential temperature. The turbulence model is the standard k-ε model. In order to improve the modeling of buildings' shapes, FAVOR method (Hirt, 1993) is incorporated using the database of effective volume ratio and open area ratio in each mesh. Heat flux from the surface of buildings and land is taken into account as source terms in the energy equation using Newton's cooling law.

The influence of trees was added to the model by inserting a drag term into the momentum transport equation and a turbulence source term into the k-ε equation (Yoshida et al., 2000, Iwata et al., 2004). Currently, the effects of evapotranspiration are not considered.

In order to efficiently calculate large scale Poisson equations, Algebraic Multigrid method (K. Stuben, 1999) is employed.

4. Results

4.1 Simulation Condition

Figure 2 shows the analyzed domain, which is 5 km (X: east-west direction) × (Y: south-north direction) × 0.5 km (Z: vertical direction) of the waterfront area of Tokyo (35°39' 50"N latitude, 139°45' 23E" longitude). The following orthogonal grid is applied to evaluate the urban terrain and topology explicitly.

- Grid spacing in X and Y directions: 5 [m] (uniform mesh)
- Grid spacing in Z direction: 1 – 10 [m] (non-uniform mesh)
- Number of grid points: 1,000 (X) × 1,000 (Y) × 100 (Z) =100,000,000

The meteorological boundary conditions of the computational domain were created by averaging the data of 23 days of fine weather in summer, which were calculated by a mesoscale meteorological model. The average location of the sun was; altitude 58.9°, azimuth 246.1°.

The boundary conditions of wind at the surface of soil and at building walls were set by the generalized logarithmic law.

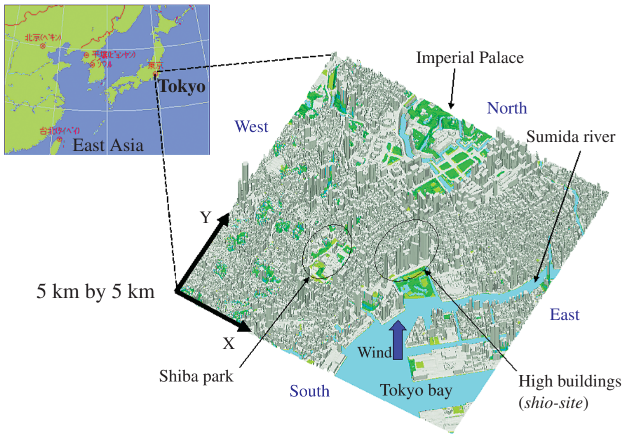

Fig. 2 Domain of the Simulation (5 km × 5 km)
Sky blue: Water (Sea, river, etc.). Yellowish green: lawn.
Green: Tree.
*Height of the buildings is emphasized.

4.2 Simulation Results

Figure 3 shows the distribution of velocity vectors and air temperature at 10 m above the ground, 100 m and 300 m above the sea level. At 300 m above the sea level, effects of distribution of urban structures are smaller; the directions of wind vectors and distribution of air temperature are almost uniform compared to those of 10 m and 100 m.

In the left figures, only the wind vectors that exceed 2 m/s are shown and at 10 m above the ground most of them are seen in open spaces, such as parks, rivers and roads. That is, "Wind paths" are formed along open spaces. In addition, air temperature is lower in these open spaces than in surrounding areas. The areas of high temperature correspond to the built up areas, where strong wind is not observed.

At 100 m above the sea level, it can be seen that the high building cluster shown in Figure 2 greatly affects wind field. A region with under 2 m/s extends about 1 km in the building cluster's wake, while regions of strong winds are formed at the sides of the cluster. At the same time, higher temperature region is formed in the cluster's wake and lower temperature region are formed at the sides of the cluster.

Although the effects of the building cluster on the thermal field are small compared to the effects on the wind filed, it is likely that air temperature in the wake of the cluster will become even higher if the effects of anthropogenic heat are considered. We are preparing a database of anthropogenic heat for use in future calculations.

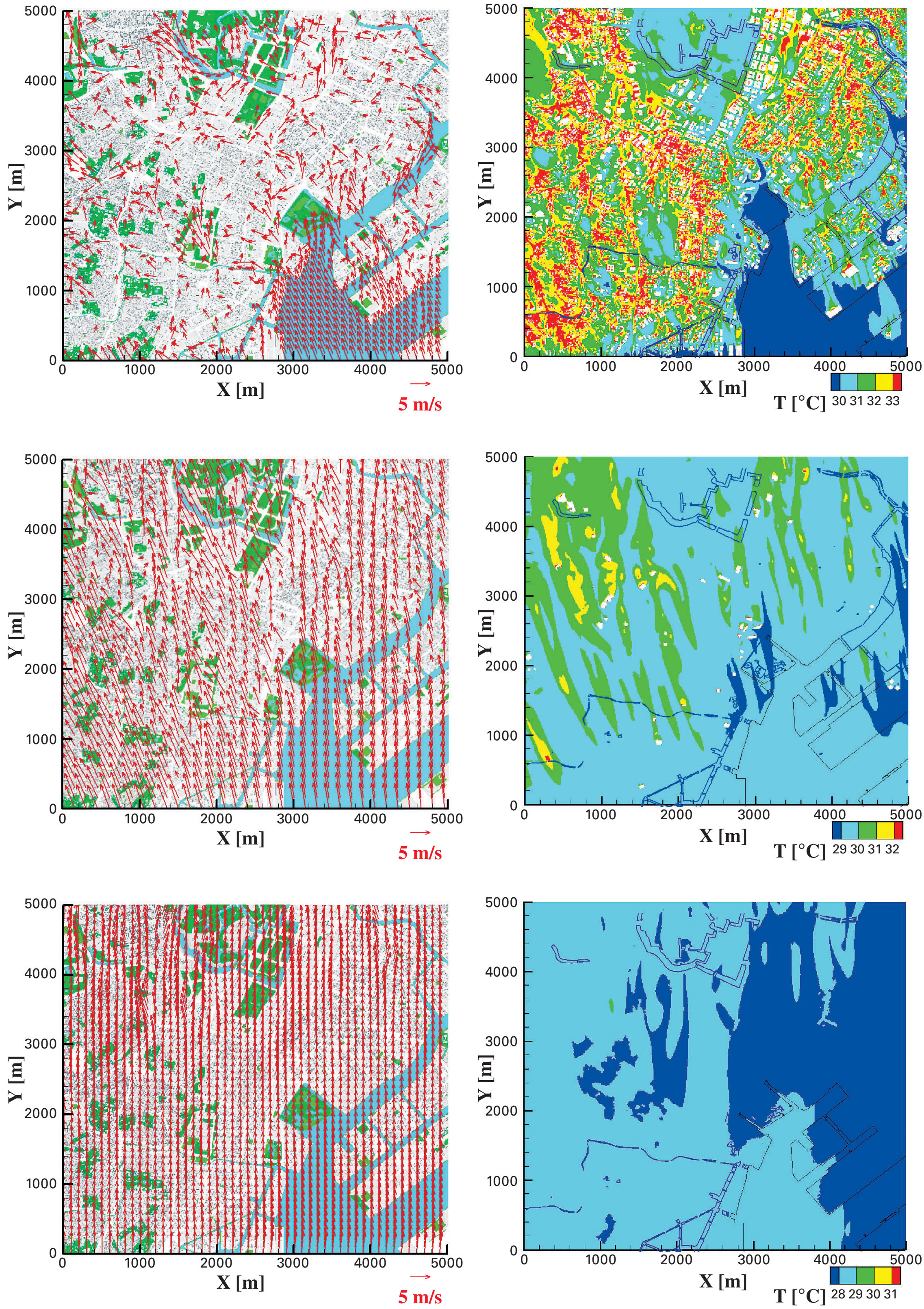

Fig. 3 Distribution of Velocity vectors (left) and air temperature (right).
Upper: 10 m above the ground, Middle: 100 m above the sea level, Bottom: 300 m above the sea level.

4.3 Comparisons to measurement

In this section, observed wind data is compared to the simulation results to confirm the validity of the analysis. The observation was performed on a typical summer day, September 3, 2004 at 14:00. In Figure 4, a comparison of wind velocity between measurement data and the CFD analysis data is shown. Wind direction in the coastal area (Area 1) and urban area (Area 2) obtained by the CFD analysis match the measurement data well. On the other hand, the mesoscale analysis matched the flow of the sea breeze in the coastal area (Area 1), but flow in the urban area (Area 2) was not well matched. This is because mesoscale model uses a uniform roughness length, and influence by the building cluster is not directly considered.

5. Summary

We developed a thermal environmental analysis system on the Earth simulator, and performed a CFD simulation of the thermal environment in the Tokyo seaside area, resolving individual buildings. As a result, it was confirmed that "wind paths" were clearly formed along open spaces such as rivers and traffic roads. It was also confirmed that high-rise building clusters create a region of stagnant flow and elevated temperatures.

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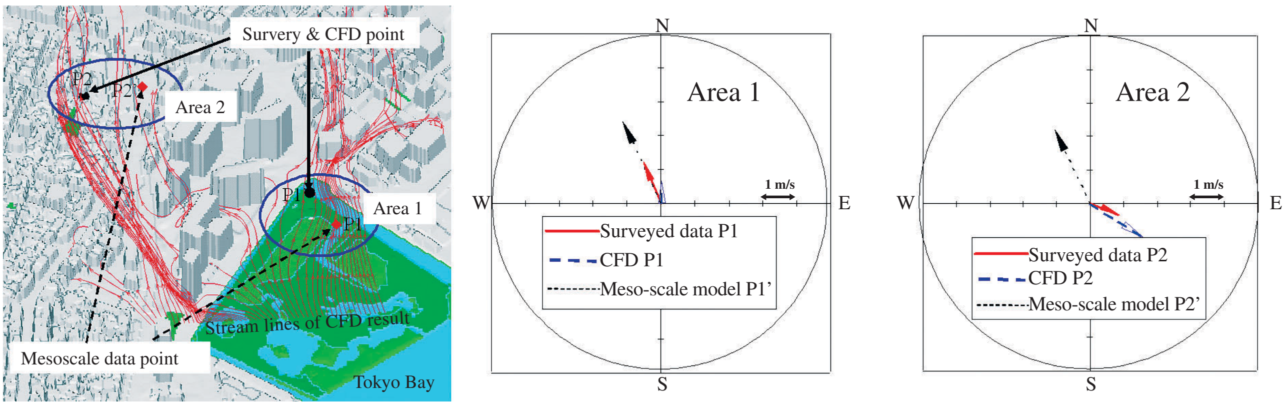

Fig. 4 Wind directions at 14:00: Surveyed result, CFD and mesoscale model.
Middle figure: Area 1 (at the seaside) . Right figure: Area 2 (in the town).

東京湾沿岸部における熱環境の数値シミュレーション

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平成17年度は、昨年度に引き続き、都市ヒートアイランドの解析に向けて、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の開発を地球シミュレータ上で進めた。FAVOR法や、樹木モデルを導入して都市構造の再現性を高めるとともに、基礎方程式に改良を施し、温位を取り扱えるようにした。同時に、都市データの整備を行い、都市部の熱環境解析の一例として、汐留の再開発エリアを含む5km四方領域のシミュレーションを実施した。特に、超高層ビル群の熱環境への影響と都市に存在する様々なスケールのオープンスペースの効果に注目して解析を行った。その結果、上空の風はほぼ南風となっているのに対して、地表付近では、道路や河川等の連続したオープンスペースに沿って風が流れていることを示した。同時に海風の移流のため、海岸近くの気温は低く現れていることが分かった。超高層ビル群は、風速場に非常に大きな影響を与えており、それに伴い気温分布も大きく影響を受ける。今後は都市の人工排熱の影響を考慮し、より総合的な解析システムに発展させる予定である。

キーワード：都市ヒートアイランド, CFD，気流，気温，都市域，高層ビル群