DEVELOPMENT OF URBAN METEOROLOGICAL MODELS FOR EVALUATION OF URBAN THERMAL ENVIRONMENT

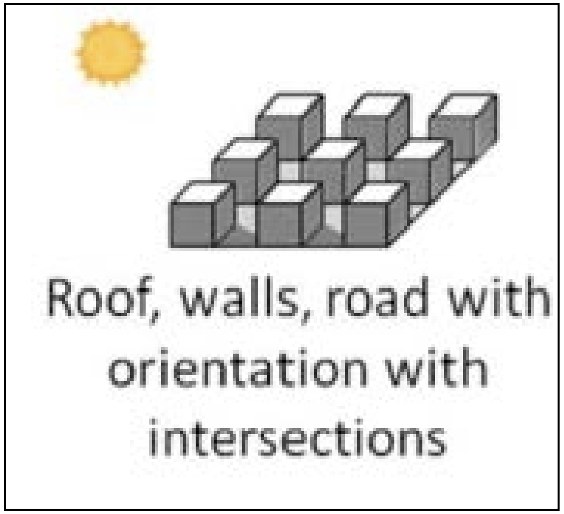
Ryosaku Ikeda

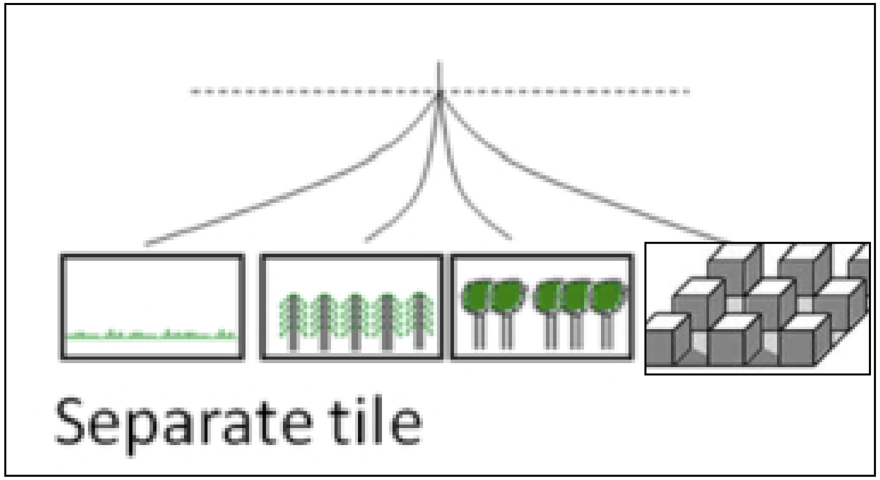
Center for Computational Sciences, Researcher

Outline

- Urban Canopy Model
- Large Eddy Simulation Model

Urban Canopy Model





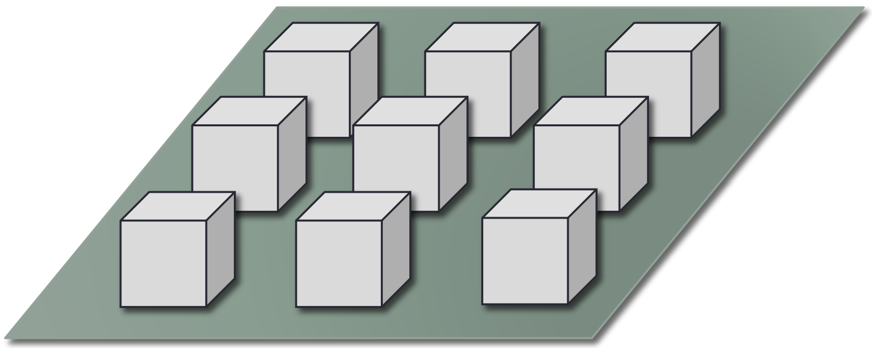
Grimmond et al. (2011), modified

- Urban canopy model accounts for
  - Building resistance,
  - building shadows, radiation reflected between buildings,
  - sky view factor, thermal inertia.

By coupling this model to a Mesoscale model, the urban thermal environment can be calculated more accurately than with the traditional slab model.

Urban Canopy Model (Ikeda and Kusaka, 2010)

3-D infinity-extended regular array

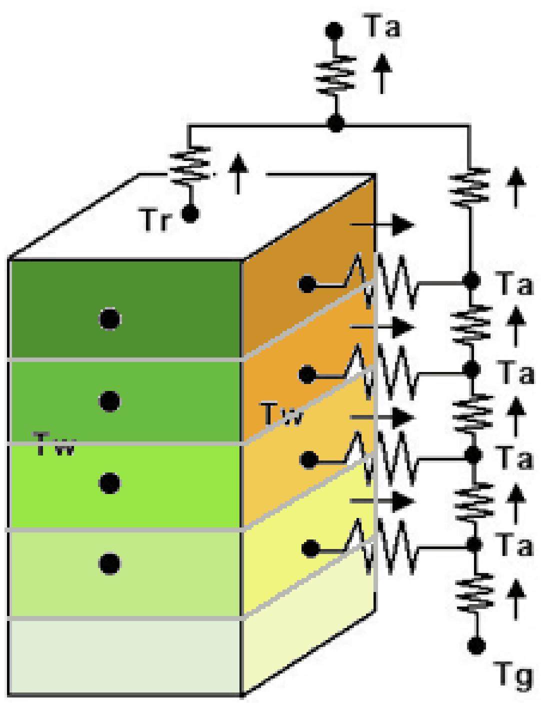


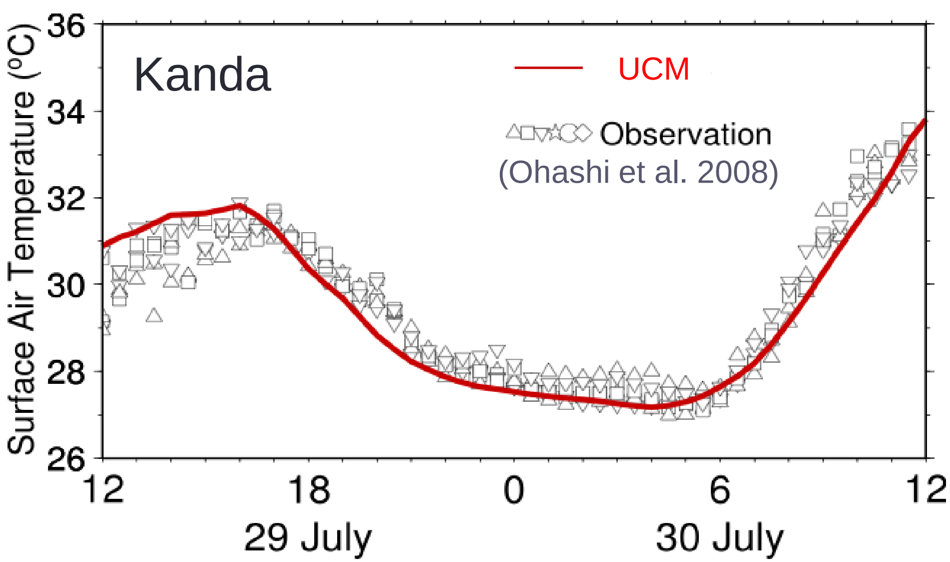
$$\frac{\partial u}{\partial t}=\frac{1}{m}\left(K_m m\frac{\partial u}{\partial z}\right)-c_d A u\sqrt{u^2+v^2}+f(v-v_g)$$

$$\frac{\partial v}{\partial t}=\frac{1}{m}\left(K_m m\frac{\partial v}{\partial z}\right)-c_d A v\sqrt{u^2+v^2}-f(u-u_g)$$

$$\frac{\partial \theta}{\partial t}=\frac{1}{m}\frac{\partial}{\partial z}\left(K_h m\frac{\partial \theta}{\partial z}\right)+\frac{Q_{AS}}{\rho c_p}$$

$$\frac{\partial q}{\partial t}=\frac{1}{m}\frac{\partial}{\partial z}\left(K_q m\frac{\partial q}{\partial z}\right)+\frac{Q_{AL}}{l\rho}$$

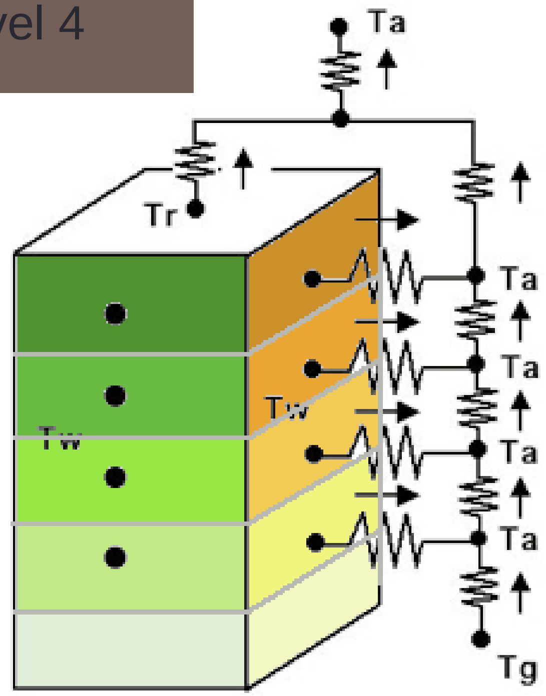




Simplification

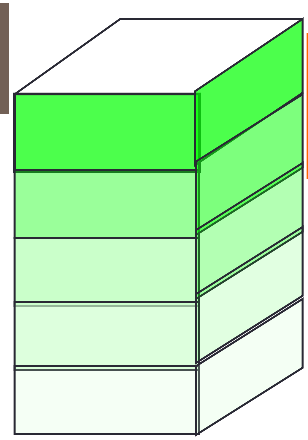
Our UCM is simplified in 3 ways,
to reduce the computational load of the heat budget calculations at the wall surface.

Level 4



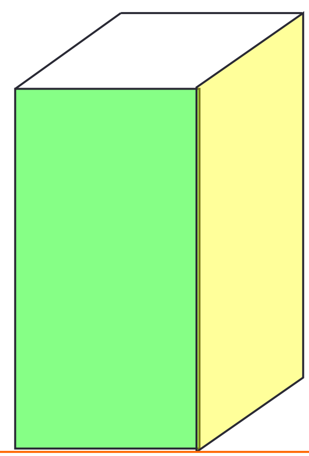
- Four directions
- Accounts vertical layers

Level 3



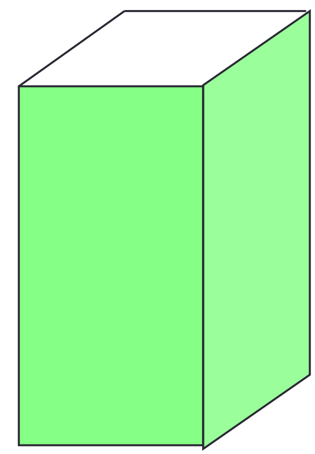
- Only accounts vertical layers

Level 2



- Four directions

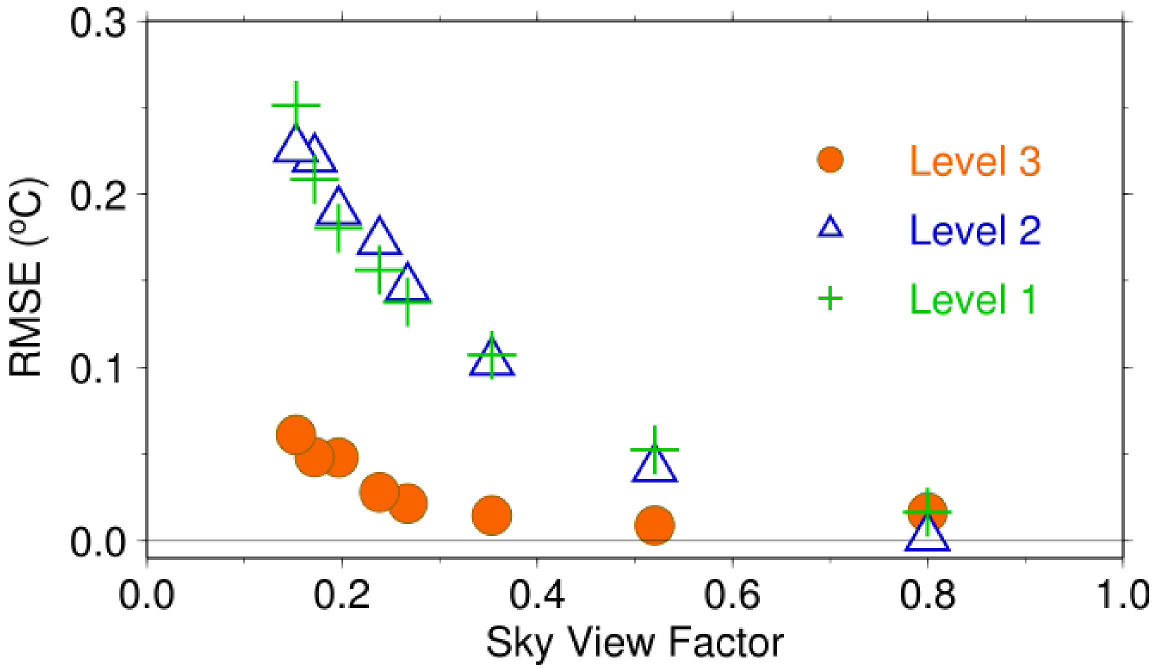
Level 1



(Ikeda and Kusaka, 2010)

Inter-comparison of the four models

The RMSE for surface air temperature in relation to the simplified Level 4 model under varying SVFs.



- The RMSE of Level 3 is very small unrelated to the SVF.
- The RMSE of Levels 2 and 1 become larger as the SVF decreases.
- From the simplification, the performance of the Level 3 model is almost equal to the Level 4 model, and the amount of memory is reduced by 57%, the CPU time is reduced by 67%.

DEVELOPMENT OF
A NEW BUILDING-RESOLVING LES MODEL

Introduction

- We have been developing Building-resolving Meteorological Model based on Large-Eddy Simulation (LES).
- We plan to perform sensitivity analyses, impact evaluations, and future projections of urban thermal environment at city-scale, using this model.

Basic Equations
– Boussinesq Approximation Equations

$$\frac{\partial \overline{u_i}}{\partial x_i} = 0$$

$$\frac{\partial \overline{u_i}}{\partial t} + \frac{\partial \overline{u_i}\,\overline{u_j}}{\partial x_j} = -c_p \theta_0 \frac{\partial \overline{\Pi'}}{\partial x_i} + \frac{\partial}{\partial x_j}\left(-\tau_{ij} + 2\nu \overline{S_{ij}}\right) + \overline{F}_i + \overline{B}\delta_{i3}$$

$$\frac{\partial \overline{\theta'}}{\partial t} + \frac{\partial \overline{u_j}\,\overline{\theta'}}{\partial x_j} = \frac{\partial}{\partial x_j}\left(-\tau_{\theta_j} + \kappa \frac{\partial \overline{\theta'}}{\partial x_j}\right) + Q$$

$$\frac{\partial \overline{q_v}}{\partial t} + \frac{\partial \overline{u_j}\,\overline{q_v}}{\partial x_j} = \frac{\partial}{\partial x_j}\left(-\tau_{q_j} + \kappa_q \frac{\partial \overline{q_v}}{\partial x_j}\right)$$

Coordinate, Grid System	Cartesian, Arakawa-C
Discretization	Finite difference method
Time Integration Scheme	3rd order Runge-Kutta method
Space difference scheme	2nd order central
Algorithm	SMAC
SGS model	Smagorinsky, Deardorff(1980)
Buildings	Mask method (Building-level resolution)
Short wave radiation	Dudhia Simple (Dudhia 1989)
Long wave radiation	RRTM (Mlawer et al. 1997)
Radiation within an urban canopy	3D refrection Take into account street trees.
Cloud physics	Warm rain

Parallelization

- In general, computational load of LES model is very large, so parallelization of the code is also performed.

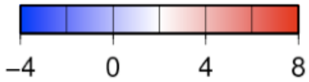
- We have been collaborating closely with the Division of High Performance Computing Systems.

(Collaborating with Prof. Boku)

- Parallel computation tests are performed on the super computer, T2K-Tsukuba.

Numerical simulation 1 –Convective Thermal

Horizontal cross-sections of vertical velocity at z=200m



m/s

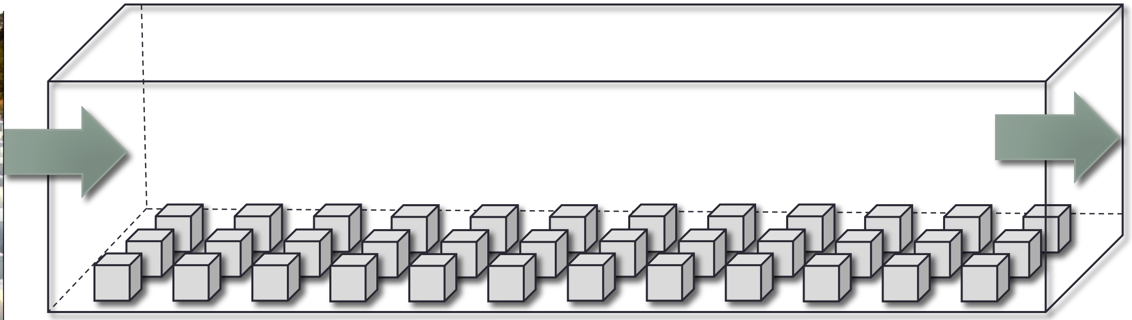
T=500[s]

T=1500[s]

T=4000[s]

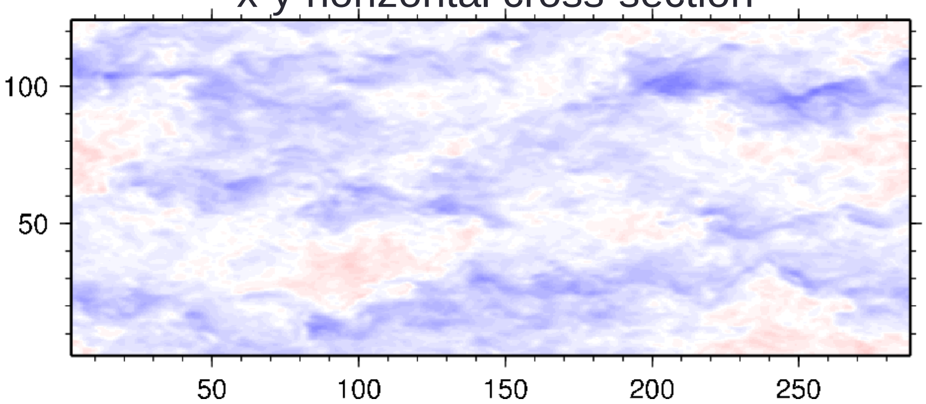
- In the first few hundred seconds of simulation, the vertical velocity field is characterized by small bubbles.
- At t = 1500s, the cell shapes are more rectangular and are about 300m in horizontal scale.
- After t=4000s , the flow is clearly composed of polygonal convective elements ranging from about 1km.

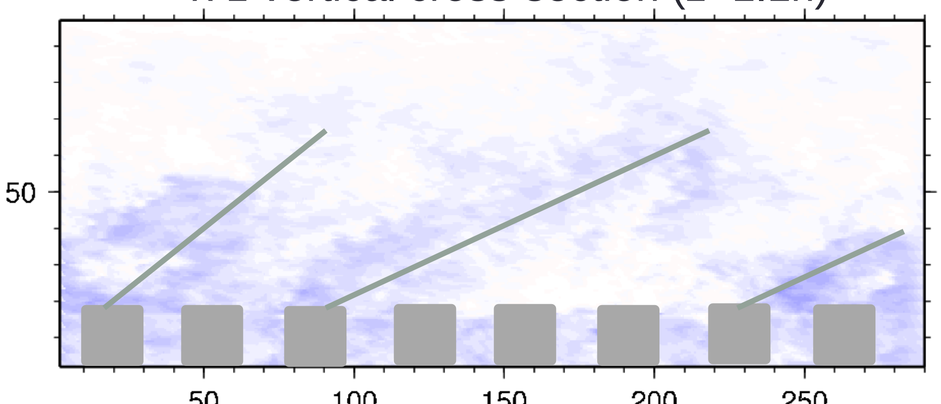
Numerical simulation 2: Flow Including cube arrays



Building	1.5m × 1.5m × 1.5m (cube)
Grid Spacing	0.1m
Upper wind velocity	2.15 [ms^{-1}]
Boundary condition	Periodic

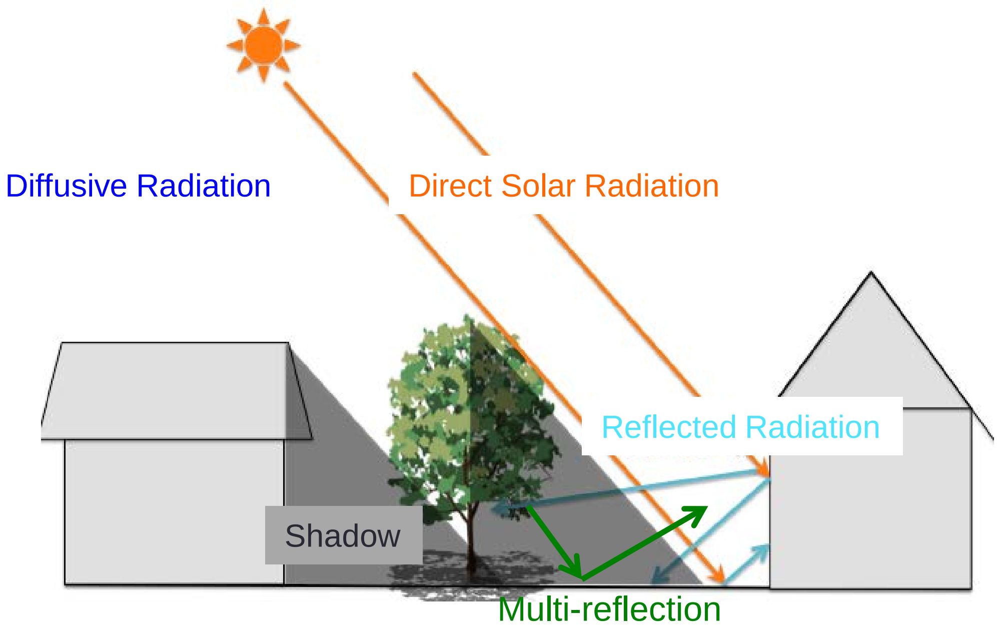
Stream-wise velocity fluctuation u" (= u − <u>)





Radiation model for an Urban Canopy

- The radiative environment is an important factor in determining local-scale temperature distribution.
- To investigate how a 3-D structure can affect urban thermal environment, we have developed an urban radiation model.

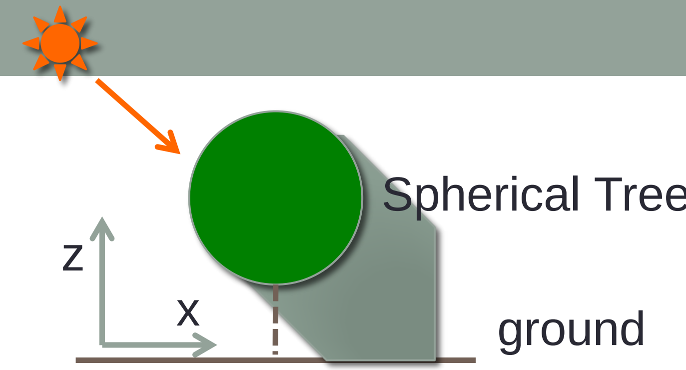


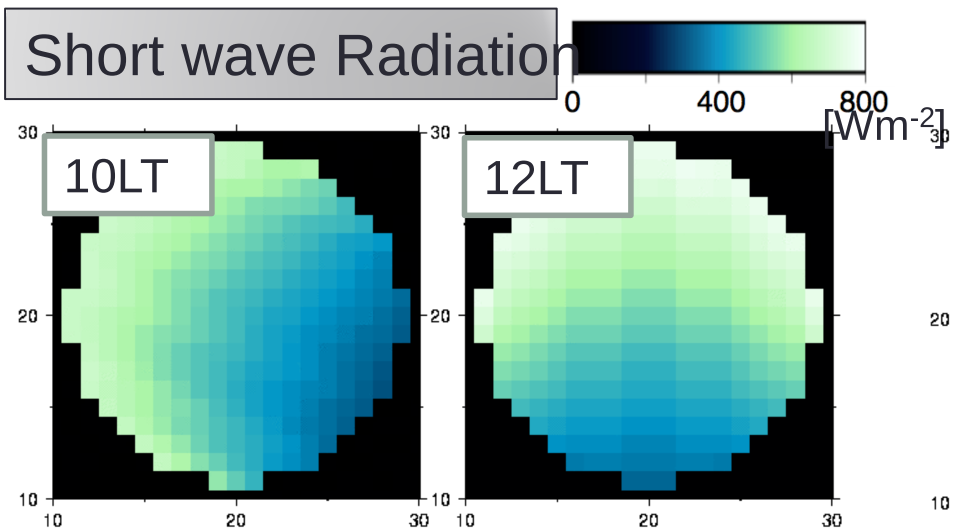
【Short wave radiation】
Direct, scatted and reflected (from buildings, ground and trees etc.) solar radiation.
【Long wave radiation】
From sky, buildings, ground, and trees.

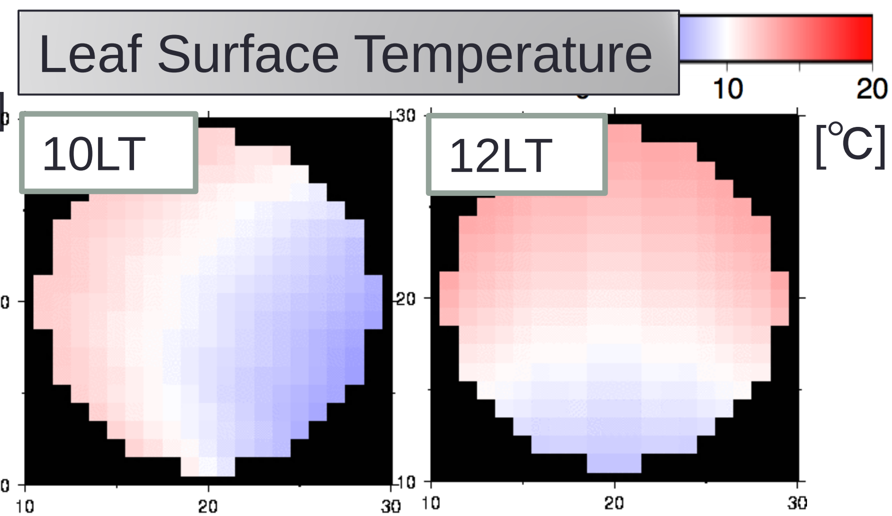
- In order to calculate the exact net radiative flux by taking an infinite number of multiple reflections into consideration.

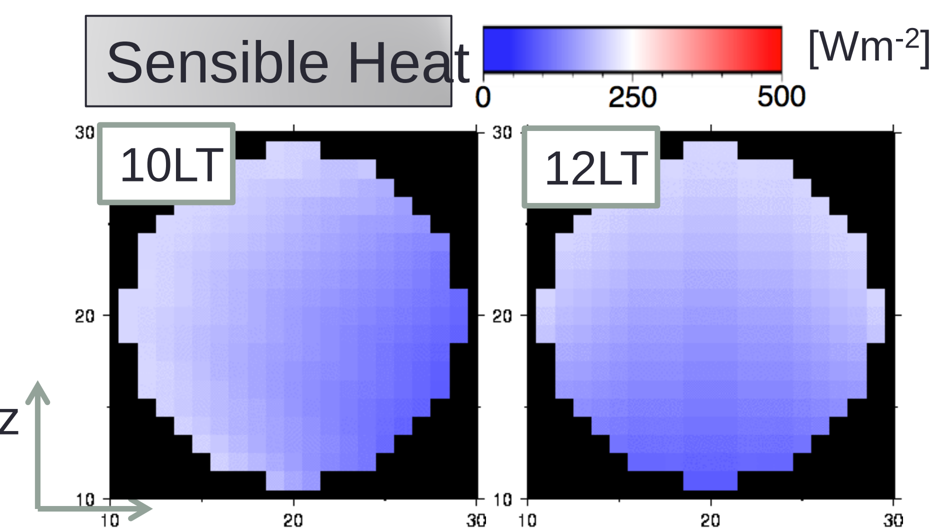
Test calculation (Single Tree)

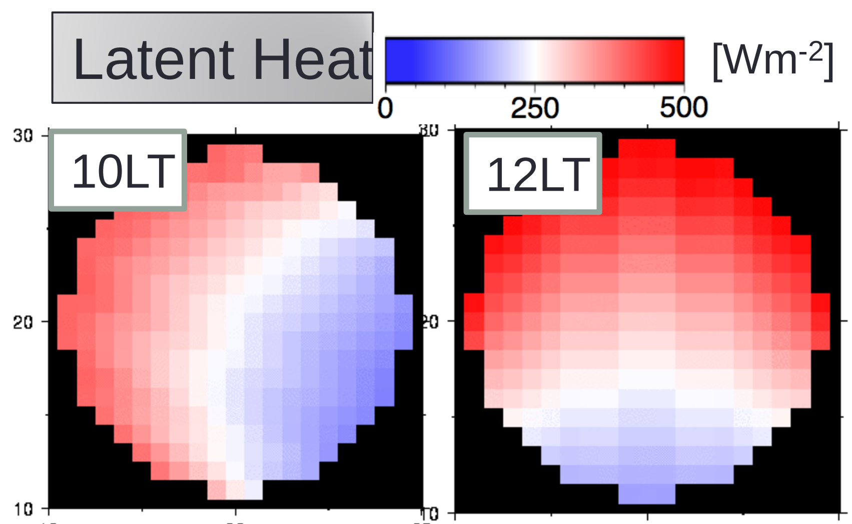
- Tree crown is Spherical. Radius is 2m.
- LAI: 0.8, Albedo: 0.15, Emissivity: 0.98



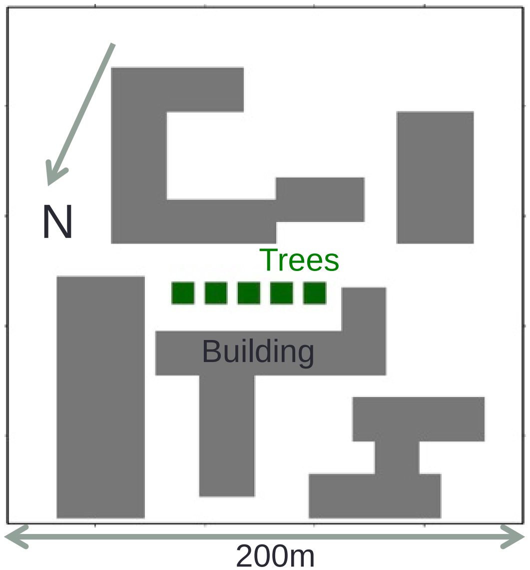






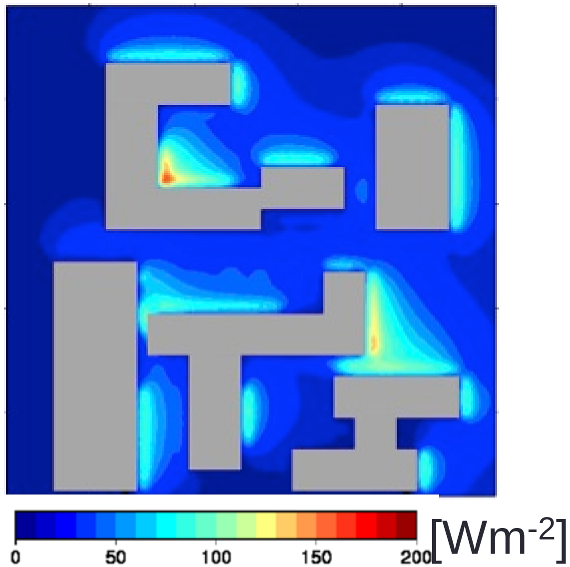


Test calculation including trees

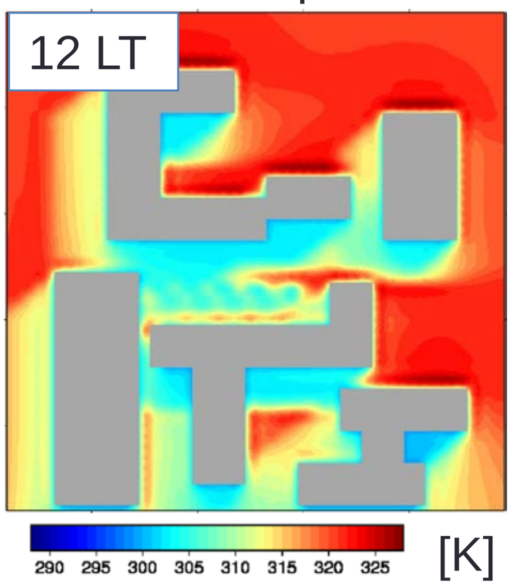


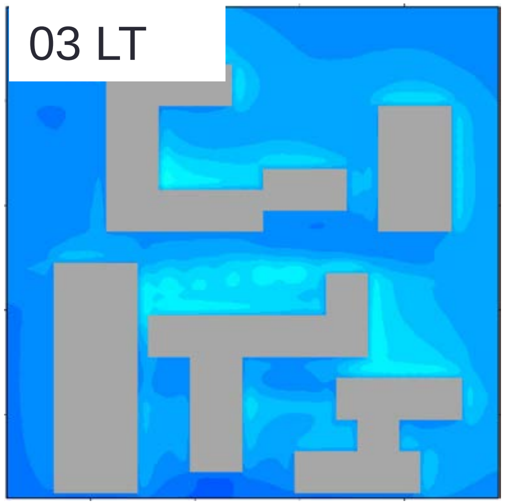
Shadow Area

Reflected radiation



Surface Temperature





Lat., Lon.	38° N, 135° E
Date	Sep. 1
Albedo	0.2
Emissivity	0.98
LAI	0.8

Summary

- We have been developing a local meteorological model based on the LES model.
- Several verification tests were performed. From these numerical test results, it can be concluded that, our model is correctly developed with regarding the dynamical core. Physics options are being implemented.
- In order to investigate how a 3-D structure can affect the urban thermal environment, we have developed an urban radiation model. Based on several test calculations, complicated radiative environments can be evaluated using this model.
- We plan to use our LES model to analyze the urban thermal environment in detail.

- We plan to perform sensitivity analyses, impact evaluations, and future projections of urban thermal environment at city-scale, using this model.
- We examine how to plan adaptation to this environmental problems.