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Large-eddy simulation of efficiency of momentum transport in spatially developing urban boundary layer

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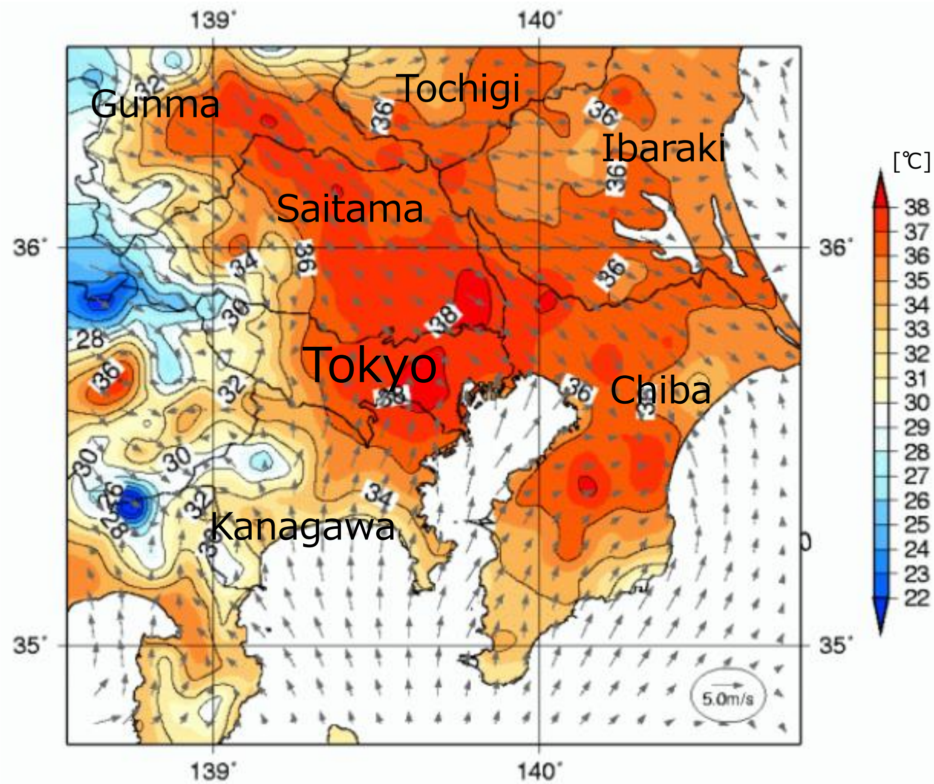
Background and objective of the research



Urban heat island

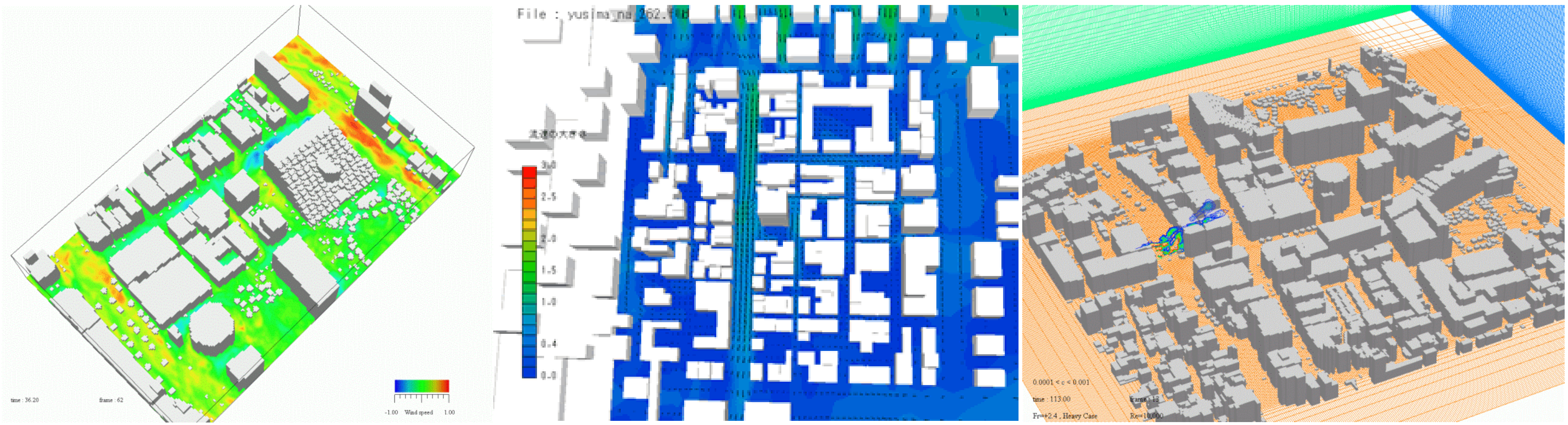
Air pollution

- Urban heat island and air pollution have become serious issues in urban spaces.
- To arrive at solutions to these problems with the design of buildings and urban spaces, it is necessary to predict the urban climate accurately.

Background and objective of the research

The problems of numerical models to predict the urban climate

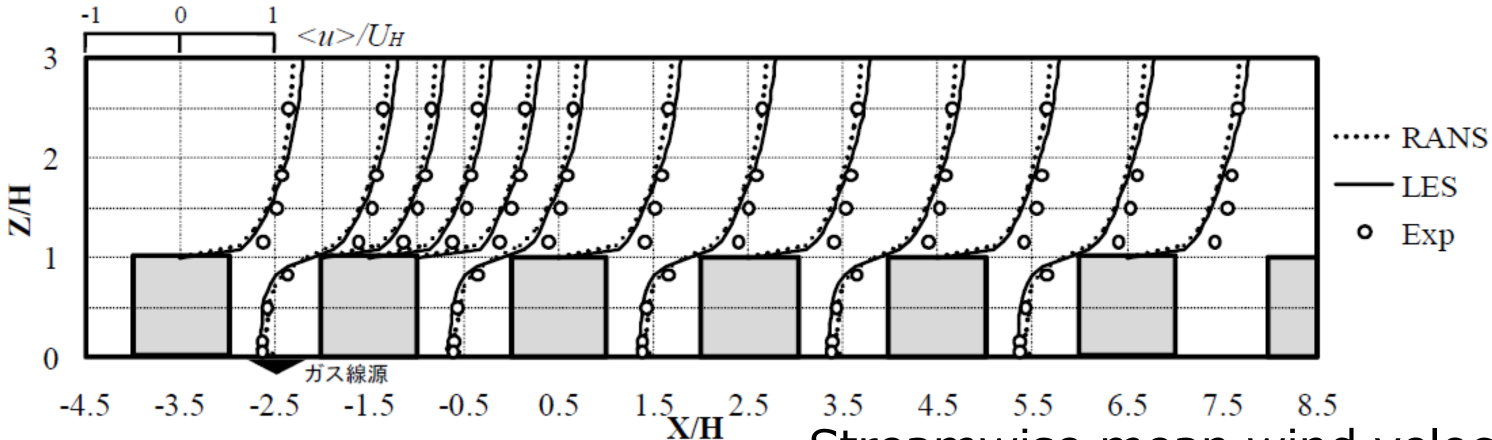
・Micro-scale models : The prediction accuracy of RANS models in an urban boundary layer. (Yoshie et al. (2012))



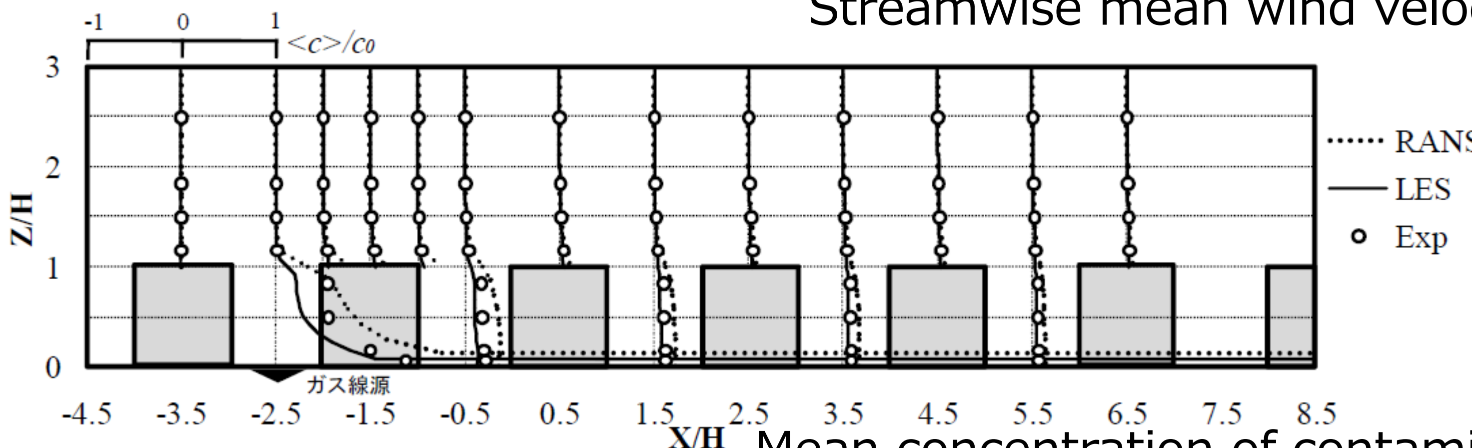
Micro-scale models
(Building scale)
(City block scale)

In this research, we focus on the investigation and the improvement of the prediction accuracy of RANS models in an urban boundary layer.

Background and objective of the research



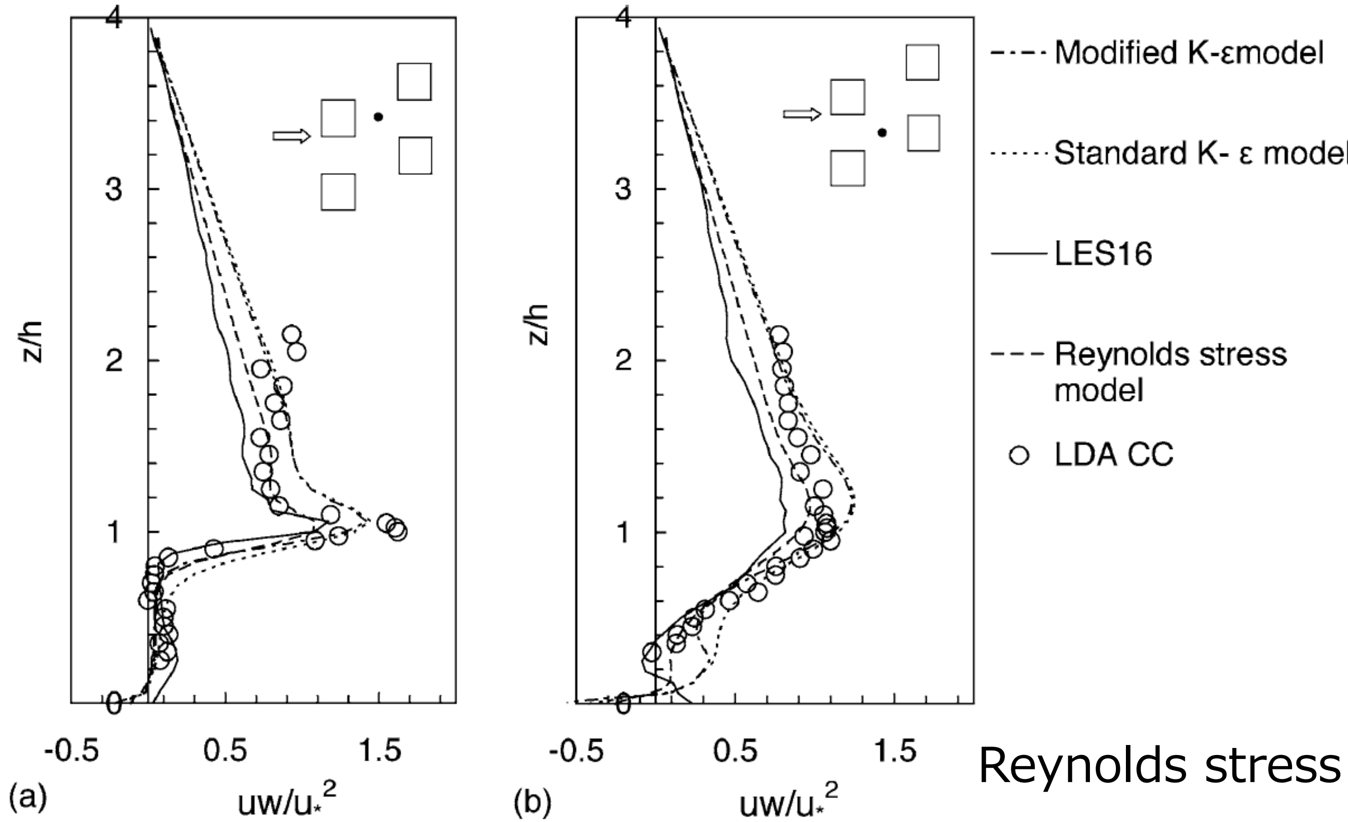
Streamwise mean wind velocity



Mean concentration of contaminant

- Yoshie et al. (2012) show that RANS model (standard k-ε model) underestimates streamwise mean wind velocity above the top of the urban canopy in an urban boundary layer.
- Yoshie et al. (2012) show that RANS model (stadard k-ε model) overestimates mean concentration of contaminant at the urban canopy layer in an urban boundary layer.

Background and objective of the research



Reynolds stress <u'w'>

- Xie and Castro (2006) show that RANS model (standard k-ε model) overestimates Reynolds stress <u'w'> above the top of the urban canopy in an urban boundary layer.
- This results show that the overestimation of Reynolds stress <u'w'> is the reason why RANS model (standard k-ε model) underestimates streamwise mean wind velocity above the top of the urban canopy in an urban boundary layer.

Background and objective of the research

$$<u'w'> = -\nu_t \frac{\partial <u>}{\partial z}$$

$$\nu_t = C_\mu \frac{k^2}{\varepsilon}$$

The reason why Reynolds stress <u’w’> is overestimated in RANS model (standard k-ε model) in an urban boundary layer.

・Eddy viscosity coefficient ν_t is overestimated in an urban boundary layer.
→ It is necessary to investigate the model coefficient C_μ of eddy viscosity coefficient ν_t.

・Gradient diffusion approximation is not correct in an urban boundary layer.
→ It is necessary to investigate the budget of Reynolds stress <u’w’>.

Background and objective of the research

In this research

to investigate the prediction accuracy of RANS model (standard k-ε model) in an urban boundary layer

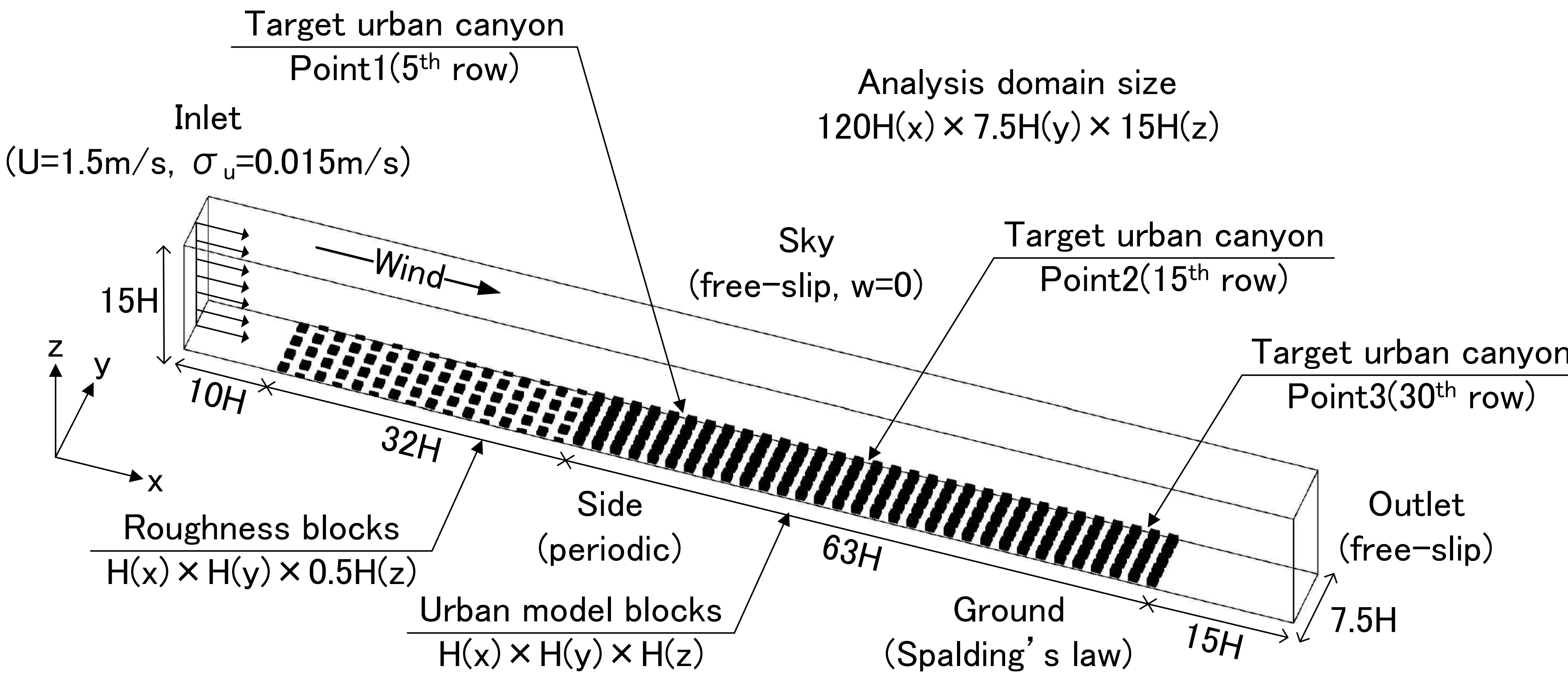
the accuracy of

- Eddy viscosity coefficient ν_t
  (Model coefficient C_μ of eddy viscosity coefficient ν_t)

- Gradient diffusion approximation
  (Budget of Reynolds stress $\langle u'w' \rangle$)

are investigated using large-eddy simulation (LES)

Analysis model and analysis condition



Target point : urban canyon center in 5^{th} row (point 1), 15^{th} row (point 2), 30^{th} row (point 3)

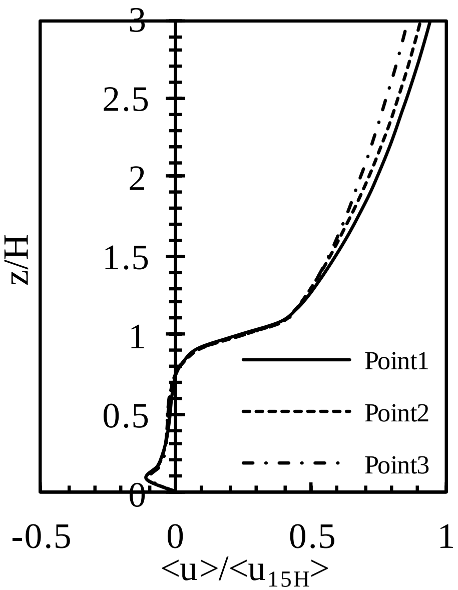
Analysis model is set up with reference to the wind tunnel experiment conducted by Uehara et al. (2000)

Analysis model and analysis condition

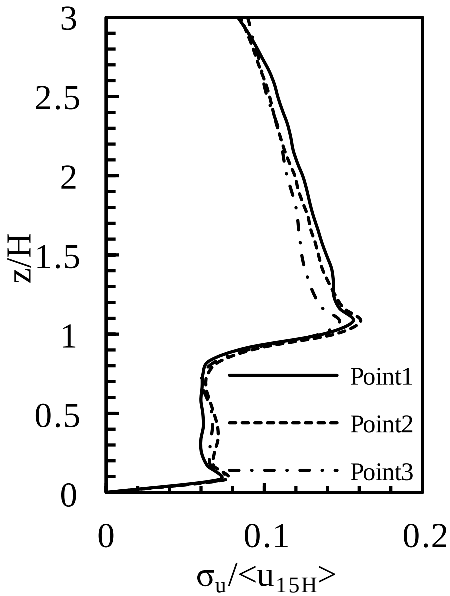
Analysis condition and boundary condition

Sub-grid scale model	Standard Smagorinsky model (C_s=0.12) van Driest damping function
Analysis grid	Analysis domain : 1440(x)×90(y)×180(z) Urban canyon : 12(x)×12(y)×12(z)
Time marching	PISO method
Poisson equation	Multi-grid method
Time discretization scheme	2nd order implicit scheme
Space discretization scheme	2nd order central difference scheme
Inlet B.C.	U=1.5m/s, σ_u=0.015m/s
Outlet B.C.	Free-slip
Side B.C.	Periodic
Top B.C.	u, v : Free-slip, w : w=0
Ground B.C.	Wall function (Spalding's law)
Building B.C.	Wall function (Spalding's law)

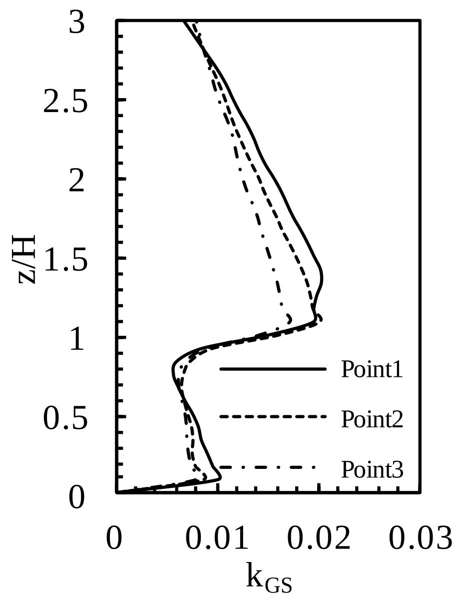
Results : Statistics of flow field



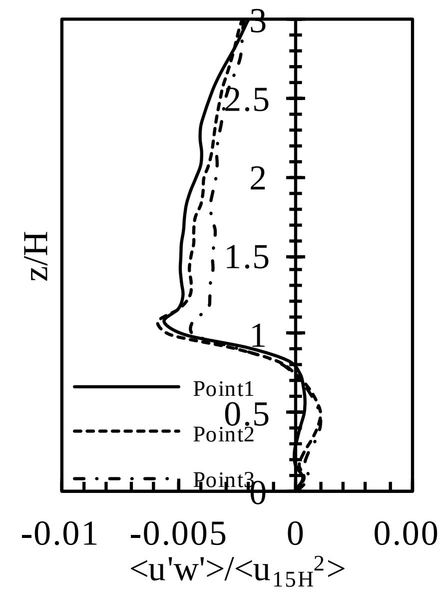
Streamwise mean wind velocity



Streamwise turbulent intensity



Turbulent kinetic energy



Reynolds stress

Urban canyon center in
5th row (point 1), 15th row (point 2), 30th row (point 3)

- As the urban boundary layer spatially develops, streamwise mean wind velocity, streamwise turbulent intensity, turbulent kinetic energy, and Reynolds stress become small above the top of the urban canopy.
- The gradient of streamwise mean wind velocity becomes the largest at the top of the urban canopy.
- Streamwise turbulent intensity, turbulent kinetic energy, and Reynolds stress become the largest at the top of the urban canopy.

Results : Estimation of model coefficient C_μ

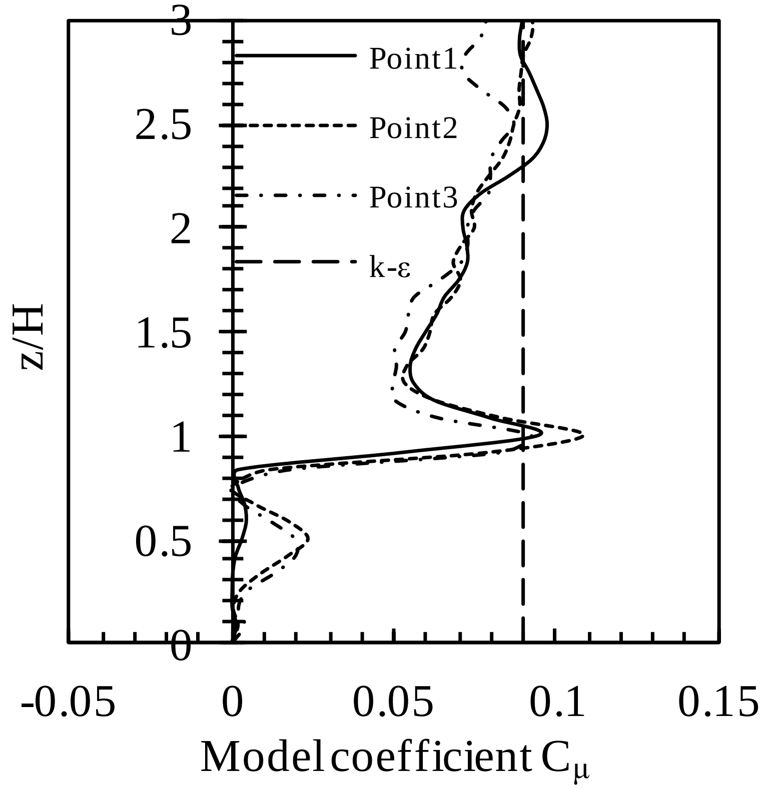
$$<u'w'> = -\nu_t \frac{\partial <u>}{\partial z} \quad (1) \qquad -<u'w'> \frac{\partial <u>}{\partial z} = \varepsilon \quad (2)$$

$$\nu_t = C_\mu \frac{k^2}{\varepsilon} \quad (3) \qquad C_\mu = \left(\frac{<u'w'>}{k} \right)^2 = 0.09 \quad (4)$$

(1) : Two dimensional shear flow and gradient diffusion approximation
(2) : Local balance of turbulent kinetic energy
(3) : Eddy viscosity coefficient ν_t derived from equation (1) and equation (2)
(4) : Model coefficient C_μ of eddy viscosity coefficient ν_t

・Model coefficient C_μ is estimated from the results of large-eddy simulation using equation (4).

Results : Estimation of model coefficient C_μ



Urban canyon center in

5^{th} row (point 1)

15^{th} row (point 2)

30^{th} row (point 3)

$$\nu_t = C_\mu \frac{k^2}{\varepsilon}$$

- Above the top of the urban canopy (from z/H=1.0 to 2.5), model coefficient C_μ becomes smaller than the value 0.09 that is used in standard k-ε model regardless of the spatial development of the urban boundary layer.
- There is some possibility that above the top of the urban canopy (from z/H=1.0 to 2.5), eddy viscosity coefficient ν_t is overestimated in standard k-ε model and the accuracy of standard k-ε model decreases regardless of the spatial development of the urban boundary layer.

Results : Budget of Reynolds stress <u’w’>

$$\frac{\partial < \overline{u_i}'\overline{u_j}' >}{\partial t} = C_{ij} + P_{ij} + \Phi_{ij} + T_{ij}^{GS} + T_{ij}^{SGS} + \Psi_{ij} + D_{ij} - \varepsilon_{ij}^{GS} - \varepsilon_{ij}^{SGS}$$

$$C_{ij} = -\frac{\partial \left\langle \overline{u_k} \right\rangle \left\langle \overline{u_i}'\overline{u_j}' \right\rangle}{\partial x_k}$$

Convection term

$$P_{ij} = -\left\langle \overline{u_i}'\overline{u_k}' \right\rangle \frac{\partial \left\langle \overline{u_j} \right\rangle}{\partial x_k} - \left\langle \overline{u_j}'\overline{u_k}' \right\rangle \frac{\partial \left\langle \overline{u_i} \right\rangle}{\partial x_k}$$

Production term

$$\Phi_{ij} = \left\langle \overline{p}' \left(\frac{\partial \overline{u_i}'}{\partial xj} + \frac{\partial \overline{u_j}'}{\partial x_i} \right) \right\rangle$$

Pressure strain correlation term

$$T_{ij}^{GS} = -\frac{\partial \left\langle \overline{u_i}'\overline{u_j}'\overline{u_k}' \right\rangle}{\partial x_k}$$

GS turbulent diffusion term

$$T_{ij}^{SGS} = -\frac{\partial \left(\left\langle \overline{u_i}'\tau'_{jk} \right\rangle + \left\langle \overline{u_j}'\tau'_{ik} \right\rangle \right)}{\partial x_k}$$

SGS turbulent diffusion term

$$\Psi_{ij} = -\frac{\partial \left\langle \overline{p}' \left(\overline{u_j}'\delta_{ik} + \overline{u_i}'\delta_{jk} \right) \right\rangle}{\partial x_k}$$

Pressure diffusion term

$$D_{ij} = \nu \frac{\partial^2 \left\langle \overline{u_i}'\overline{u_j}' \right\rangle}{\partial x_k^2}$$

Molecular diffusion term

$$\varepsilon_{ij}^{GS} = 2\nu \left\langle \frac{\partial \overline{u_i}'}{\partial x_k} \frac{\partial \overline{u_j}'}{\partial x_k} \right\rangle$$

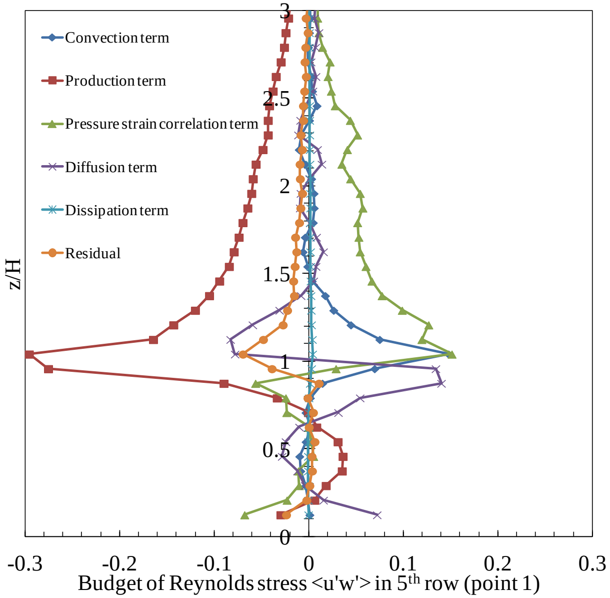
GS dissipation term

$$\varepsilon_{ij}^{SGS} = -\left\langle \tau'_{ik} \frac{\partial \overline{u_j}'}{\partial x_k} \right\rangle - \left\langle \tau'_{jk} \frac{\partial \overline{u_i}'}{\partial x_k} \right\rangle$$

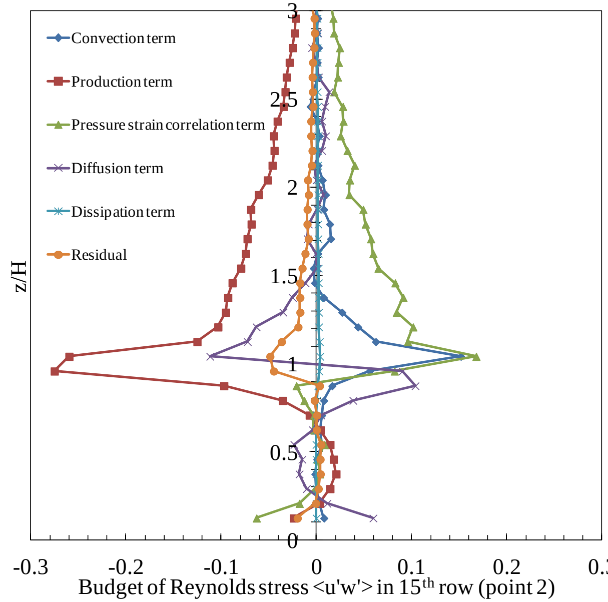
SGS dissipation term

$$C_{13} + P_{13} + \Phi_{13} + T_{13}^{GS} + T_{13}^{SGS} + \Psi_{13} + D_{13} - \varepsilon_{13}^{GS} - \varepsilon_{13}^{SGS} + Residual = 0$$

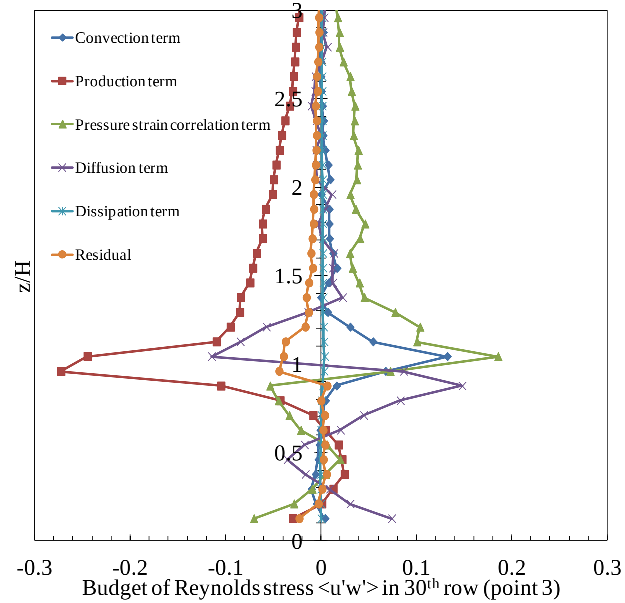
Results : Budget of Reynolds stress <u'w'>



5th row (point 1)



15th row (point 2)



30th row (point 3)

Urban canyon center in
5th row (point 1), 15th row (point 2), 30th row (point 3)

- As the urban boundary layer spatially develops, above the top of the urban canopy (from z/H=1.0 to 1.5), not only production term but also diffusion term becomes large and contribute to the increase of <u'w'>.
- There is some possibility that as the urban boundary layer spatially develops, above the top of the urban canopy (from z/H=1.0 to 1.5), the accuracy of gradient diffusion approximation of Reynolds stress <u'w'> decreases as the urban boundary layer spatially develops.

Conclusion

- Large-eddy simulation is performed to investigate the prediction accuracy of RANS model (standard k-ε model) in spatially developing urban boundary layer.

- Above the top of the urban canopy (from z/H=1.0 to 2.5), model coefficient C_μ becomes smaller than the value 0.09 that is used in standard k-ε model regardless of the spatial development.

- As the urban boundary layer spatially develops, above the top of the urban canopy (from z/H=1.0 to 1.5), not only production term but also diffusion term becomes large and contributes to the increase of <u’w’>.

- There is some possibility that above the top of the urban canopy, the accuracy of eddy viscosity coefficient ν_t and the accuracy of gradient diffusion approximation of <u’w’> decreases.