Turbulence and pollutant transport in urban street canyons under stable stratification: a large-eddy simulation

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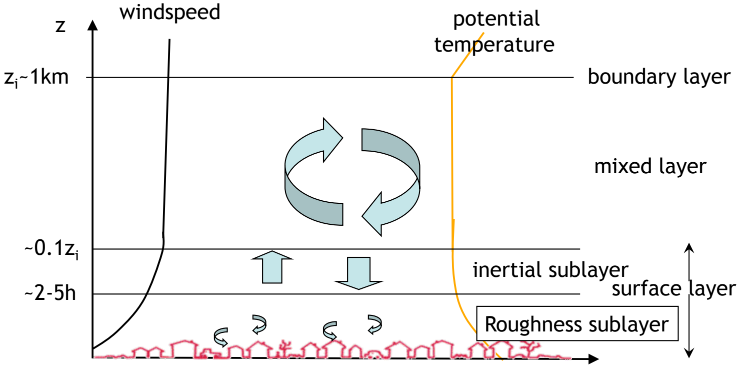
Outline

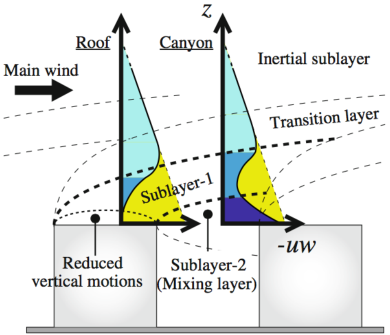
Outline

Atmospheric Boundary Layer



Street canyon

- Street canyon is the basic geometry unit of urban areas;
- Many mesoscale weather and climate models (e. g., Weather Research and Forecasting, WRF) are using (2D) street canyons as the representative elements of urban areas.
- 2D street canyon (i.e., wind blowing from a direction perpendicular to the street axis) represents the worst scenario for pollutant dispersion.



Thermal stratification

- Thermal stratification (due to solar radiation, release of stored heat, anthropogenic heat etc.) plays an important role in the air flow and pollutant dispersion processes;
- During the field measurement carried out by Niachou et al. (2008), unstable weather conditions were measured in 85% of the cases in the day period, while during the night this value was still 64%;
- During nighttime, the (long wave) radiative cooling can create a stable stratification in the atmosphere boundary layer.
- Therefore, it is very important to study the effect of different thermal stratifications on the urban environment, especially the flow and pollutant dispersion in street canyons.

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Governing equations (filtered and dimensionless)

Navier-Stokes equations:

$$\frac{\partial \overline{u}_i}{\partial t} + \frac{\partial}{\partial x_j}\overline{u}_i\overline{u}_j = -\frac{\partial \overline{p}}{\partial x_i} - \frac{\partial \tau_{ij}}{\partial x_j} + \frac{1}{Re}\frac{\partial^2 \overline{u}_i}{\partial x_j \partial x_j} + g\overline{\theta}\delta_{i3},$$

Transport equation for subgrid-scale (SGS) turbulent kinetic energy (TKE):

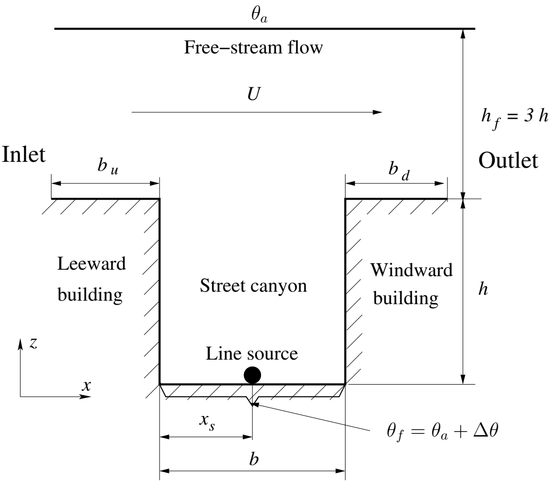
$$\frac{\partial k_{sgs}}{\partial t} + \overline{u}_i\frac{\partial k_{sgs}}{\partial x_i} = P + B - \varepsilon + \frac{\partial}{\partial x_i}\left(\frac{2}{Re_{\mathrm{T}}}\frac{\partial k_{sgs}}{\partial x_i}\right),$$

Transport equation for scalars (Temperature or pollutant):

$$\frac{\partial \overline{\theta}}{\partial t} + \frac{\partial}{\partial x_i}\overline{u}_i\overline{\theta} = -\frac{\partial \pi_i}{\partial x_i} + \frac{1}{RePr}\frac{\partial^2 \overline{\theta}}{\partial x_i \partial x_i},$$

$$\pi_i = -\nu_\theta \frac{\partial \overline{\theta}}{\partial x_i}.$$

Computational domain



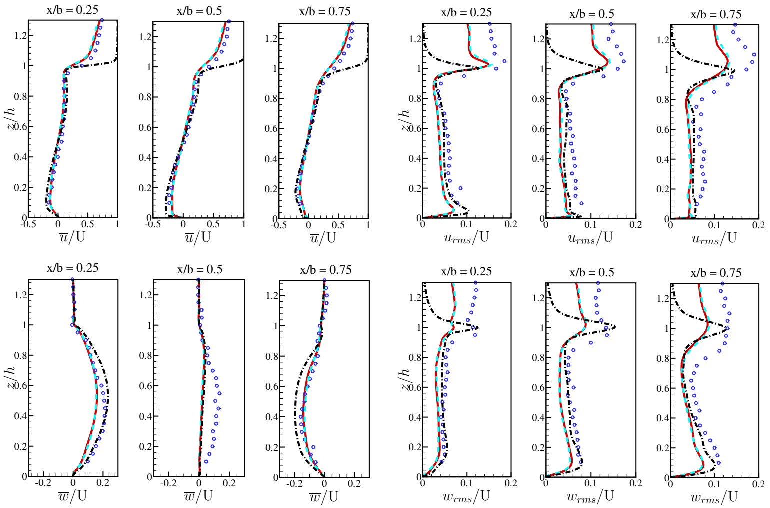
$$Ri = -\frac{gh}{\mathrm{U}^2}\frac{\Delta\theta}{\theta_a}$$

Ri = -0.1, 0, 0.09, and 0.188

B.C.

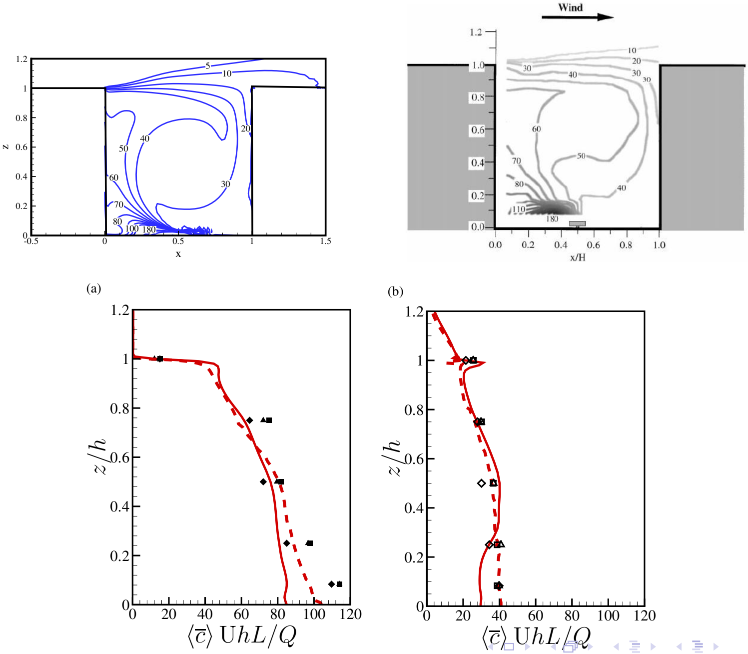
- x, y: periodic
- z top: shear free
- walls: no slip
- inlet scalars: zero
- outlet scalars: convective

Model validation: $Ri = 0$

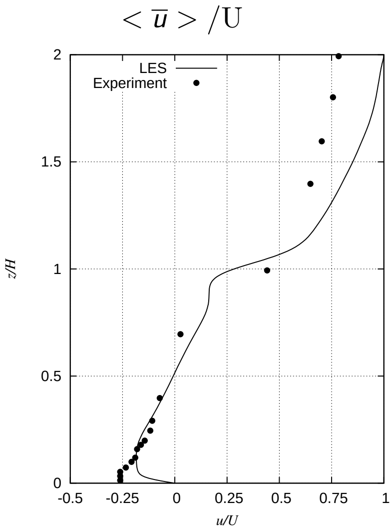


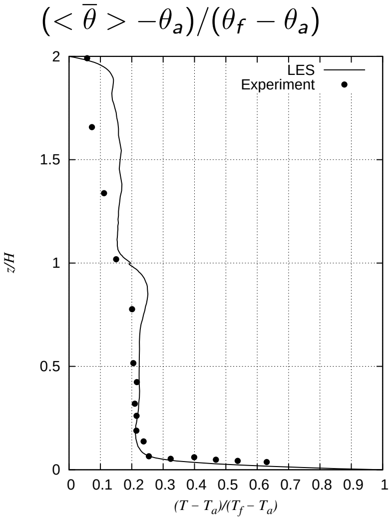
(Li et.al., 2008)

Model validation: pollutant, $Ri = 0$



Model validation: flow and temperature, $Rb = 0.3$





Experiment data are from Uehara et.al.(2000, AE).

Li et.al.(2010), BLM

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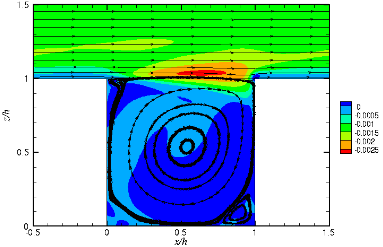
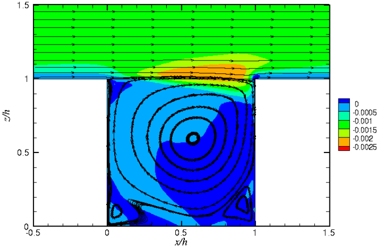
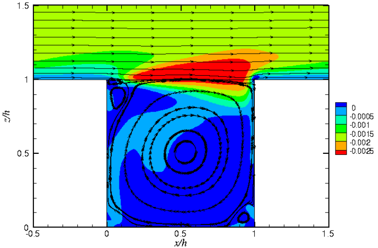
Reynolds stress $< u''w'' > /\mathrm{U}^2$



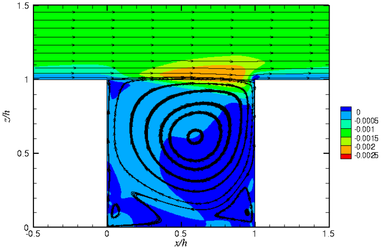
$Ri = 0$



$Ri = 0.1$

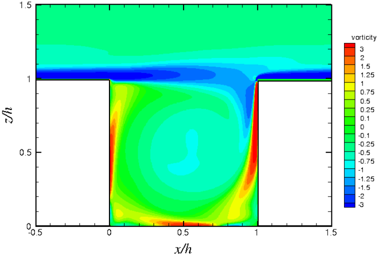


$Ri = -0.1$

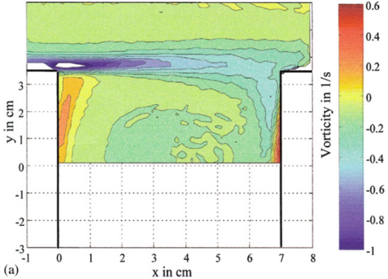


$Ri = 0.188$

Spanwise vorticity $\xi_y = \frac{\partial <\overline{w}>}{\partial x} - \frac{\partial <\overline{u}>}{\partial z}$

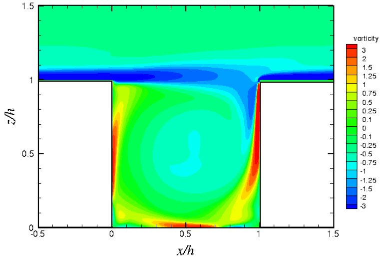


$Ri = 0$

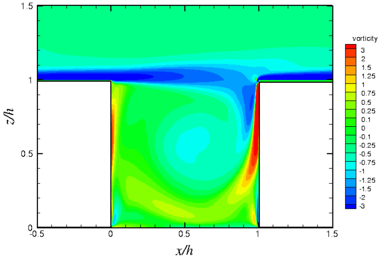


Exp (Canton et.al, 2003, AE)

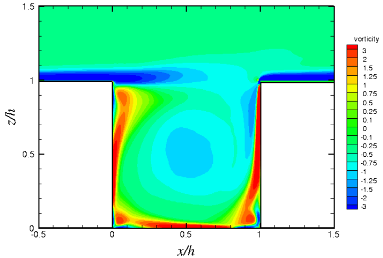
Spanwise vorticity $\xi_y = \frac{\partial <\overline{w}>}{\partial x} - \frac{\partial <\overline{u}>}{\partial z}$



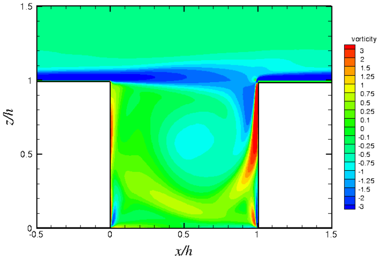
$Ri = 0$



$Ri = 0.1$

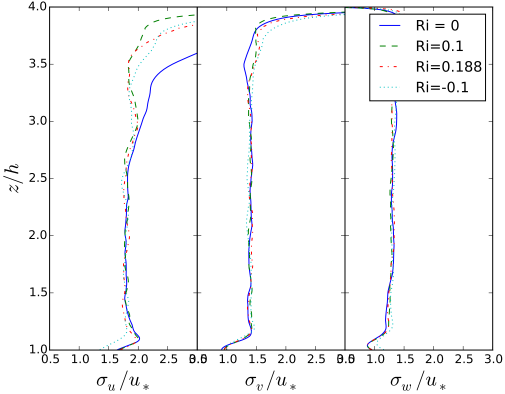


$Ri = -0.1$



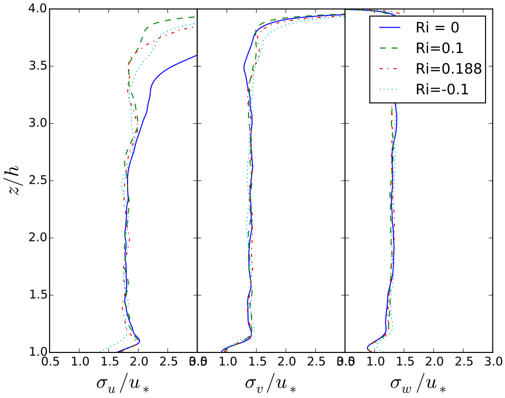
$Ri = 0.188$

Velocity fluctuations normalized by local u_*



$$u_{rms}/u_* \approx 1.8 \quad v_{rms}/u_* \approx 1.42 \quad w_{rms}/u_* \approx 1.3$$

Velocity fluctuations normalized by local u_*

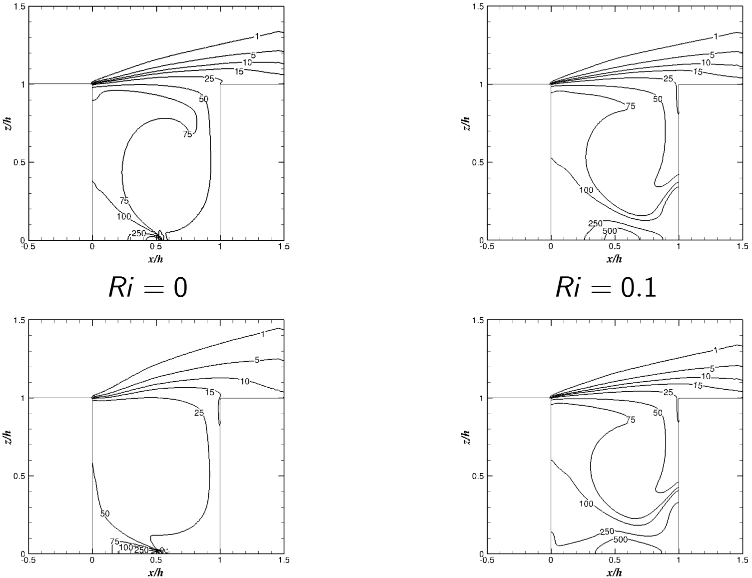


$$u_{rms}/u_* \approx 1.8 \quad v_{rms}/u_* \approx 1.42 \quad w_{rms}/u_* \approx 1.3$$

Observations in real urban areas

$$u_{rms}/u_* \approx 2.40 \quad v_{rms}/u_* \approx 1.91 \quad w_{rms}/u_* \approx 1.27$$

Pollutant concentration $<\overline{c}> UhL/Q$



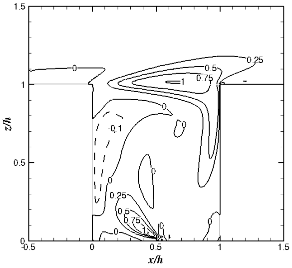
$Ri = 0$ $\quad$ $Ri = 0.1$

$Ri = -0.1$ $\quad$ $Ri = 0.188$

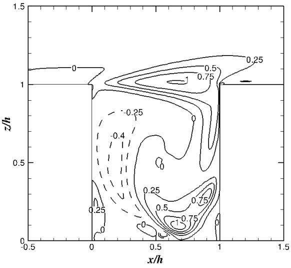
Pollutant $<\overline{c}> \mathrm{U}hL/Q$ within street canyon

Ri	Pollutant in the street canyon
-0.1	36.07
0	75.61
0.1	109.16
0.188	142.06

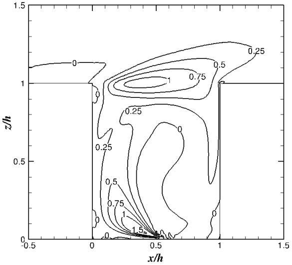
Pollutant flux $< w''c'' > hL/Q$



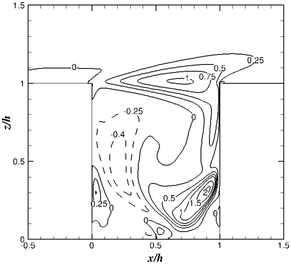
$Ri = 0$



$Ri = 0.1$



$Ri = -0.1$



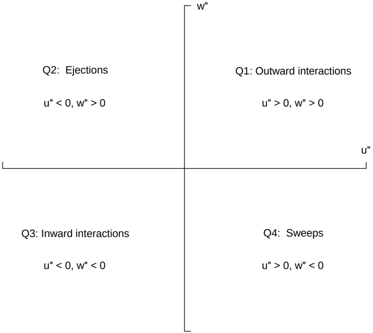
$Ri = 0.188$

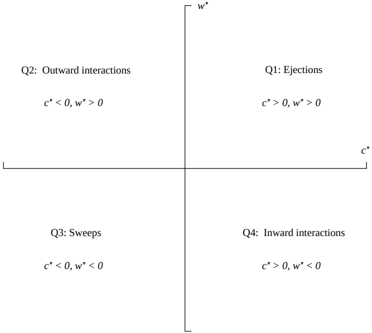
Outline

Quadrant analysis

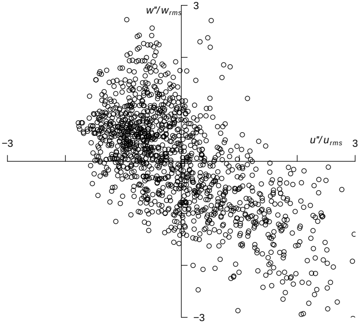
$$u = < u > + u''$$

$$c = < c > + c''$$

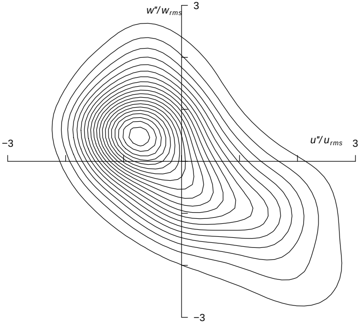




Quadrant analysis u"w", Ri = 0, Joint PDF

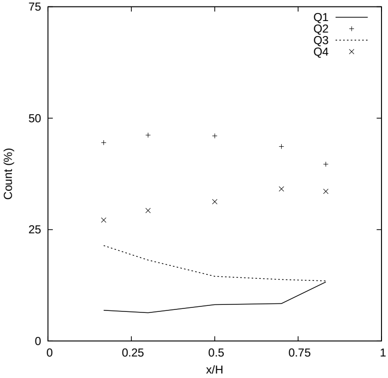


Scatter plot

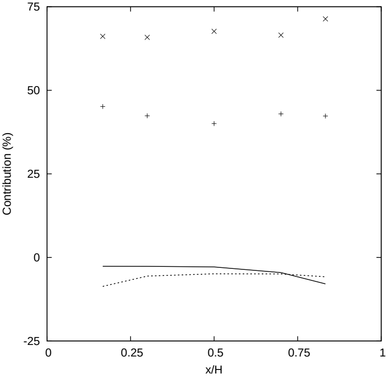


Joint PDF

Quadrant analysis u''w'', Ri = 0, along roof level

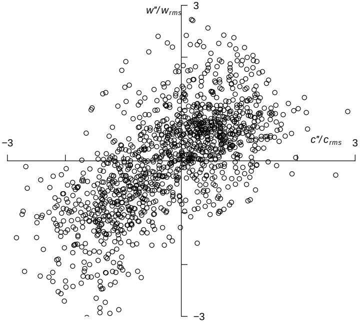


Event count

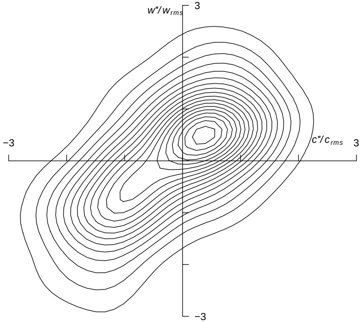


Contribution to $< u''w'' >$

Quadrant analysis w"c", Ri = 0, Joint PDF

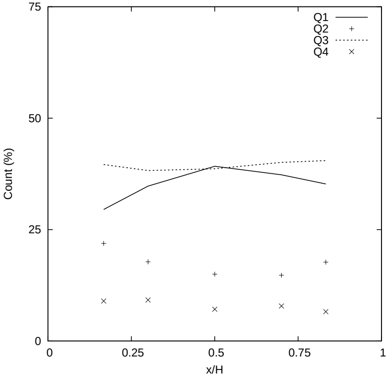


Scatter plot

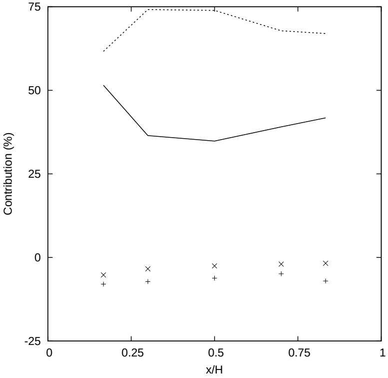


Joint PDF

Quadrant analysis w"c", Ri = 0, along roof level

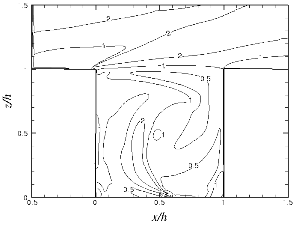


Event count

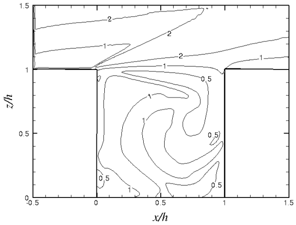


Contribution to $< w''c'' >$

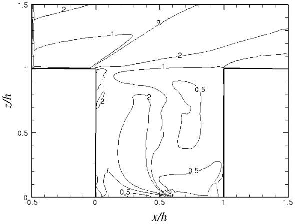
Quadrant analysis w''c'', Q1/Q3



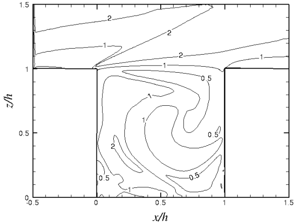
$Ri = 0$



$Ri = 0.1$

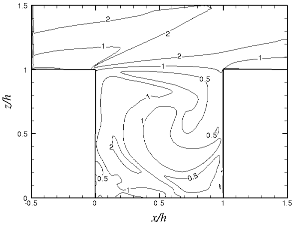


$Ri = -0.1$

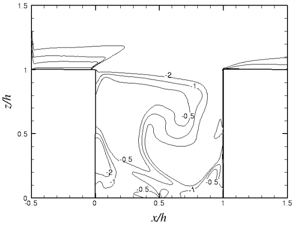


$Ri = 0.188$

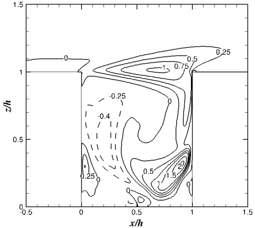
Quadrant analysis w''c'', $Ri = 0.188$



Q1/Q3

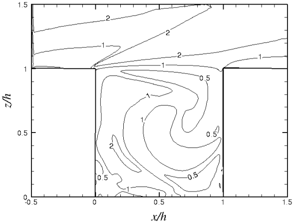


Q1/Q4

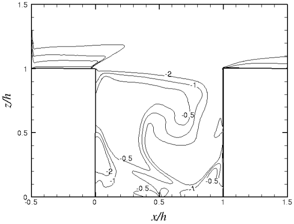


$< w''c'' >$

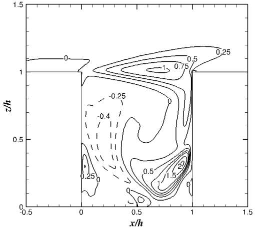
Quadrant analysis w''c'', $Ri = 0.188$



Q1/Q3



Q1/Q4



$< w''c'' >$

Q4 > Q1 > Q3 in magnitude

Outline

Summary

- Thermal buoyancy has strong effect on the turbulence and pollutant transport in urban street canyons; mixing and transport processes;
- Coherent turbulence structures are observed in street canyons and play important roles in transport and mixing processes
- Under stable stratification, the unorganized turbulent structure dominates the pollutat flux, thus reducing the pollutant dispersion from the urban canopy layer.

Acknowledgment

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