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

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Outline

1. Background
2. The model
3. Street canyons under different stratifications
4. Turbulence structure in street canyons
5. Summary
Atmospheric Boundary Layer

- Boundary layer
- Mixed layer (~2-5h)
- Roughness sublayer (zi ~ 1km)
- Windspeed
- Potential temperature
- Inertial sublayer
- Surface layer

Diagram showing the depth and characteristics of the Atmospheric Boundary Layer with various sublayers and their respective depths and properties.
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):

\[
\frac{\partial k_{sgs}}{\partial t} + \overline{u}_i \frac{\partial k_{sgs}}{\partial x_i} = P + B - \varepsilon + \frac{\partial}{\partial x_i} \left( \frac{2}{Re_T} \frac{\partial k_{sgs}}{\partial x_i} \right),
\]

Transport equation for scalars (Temperature or pollutant):

\[
\frac{\partial \overline{\theta}}{\partial t} + \frac{\partial}{\partial x_i} \overline{u}_i \overline{\theta} = -\frac{\partial \pi_i}{\partial x_i} + \frac{1}{Re Pr} \frac{\partial^2 \overline{\theta}}{\partial x_i \partial x_i},
\]

\[
\pi_i = -\nu_\theta \frac{\partial \overline{\theta}}{\partial x_i}.
\]
Computational domain

\[
Ri = -\frac{gh \Delta \theta}{U^2 \theta_a}
\]

\(Ri = -0.1, 0, 0.09, \text{ and } 0.188\)

**B.C.**
- \(x, y: \text{ periodic}\)
- \(z \text{ top: shear free}\)
- \(\text{walls: no slip}\)
- \(\text{inlet scalars: zero}\)
- \(\text{outlet scalars: convective}\)
Model validation: $Ri = 0$

(Li et al., 2008)
Model validation: pollutant, \( Ri = 0 \)
Model validation: flow and temperature, $Rb = 0.3$

\[ \frac{\langle \bar{u} \rangle}{U} \]

\[ \frac{(\langle \bar{\theta} \rangle - \theta_a)}{(\theta_f - \theta_a)} \]

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

Li et al. (2010), BLM
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Reynolds stress $< u'' w'' > / U^2$

$Ri = 0$

$Ri = 0.1$

$Ri = -0.1$

$Ri = 0.188$
Spanwise vorticity $\xi_y = \frac{\partial \langle w \rangle}{\partial x} - \frac{\partial \langle u \rangle}{\partial z}$

$Ri = 0$

Exp (Canton et.al, 2003, AE)
Spanwise vorticity $\xi_y = \frac{\partial \langle w \rangle}{\partial x} - \frac{\partial \langle u \rangle}{\partial z}$

$Ri = 0$

$Ri = 0.1$

$Ri = -0.1$

$Ri = 0.188$
Velocity fluctuations normalized by local $u_*$

\[ \frac{u_{rms}}{u_*} \approx 1.8 \quad \frac{v_{rms}}{u_*} \approx 1.42 \quad \frac{w_{rms}}{u_*} \approx 1.3 \]
Velocity fluctuations normalized by local $u_*$

\[ \begin{align*}
\sigma_{u}/u_* &\approx 1.8 \\
\sigma_{v}/u_* &\approx 1.42 \\
\sigma_{w}/u_* &\approx 1.3
\end{align*} \]

Observations in real urban areas

\[ \begin{align*}
\sigma_{u}/u_* &\approx 2.40 \\
\sigma_{v}/u_* &\approx 1.91 \\
\sigma_{w}/u_* &\approx 1.27
\end{align*} \]
Pollutant concentration $< \bar{c} > \ U h L / Q$

\[ Ri = 0 \]

\[ Ri = 0.1 \]

\[ Ri = -0.1 \]

\[ Ri = 0.188 \]
Pollutant $< \bar{c} > U_h L/Q$ within street canyon

<table>
<thead>
<tr>
<th>$Ri$</th>
<th>Pollutant in the street canyon</th>
</tr>
</thead>
<tbody>
<tr>
<td>$-0.1$</td>
<td>36.07</td>
</tr>
<tr>
<td>0</td>
<td>75.61</td>
</tr>
<tr>
<td>0.1</td>
<td>109.16</td>
</tr>
<tr>
<td>0.188</td>
<td>142.06</td>
</tr>
</tbody>
</table>
Pollutant flux \( < w'' c'' > hL/Q \)

\[ Ri = 0 \]

\[ Ri = 0.1 \]

\[ Ri = -0.1 \]

\[ Ri = 0.188 \]
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Quadrant analysis

\[ u = \langle u \rangle + u'' \]

\[ c = \langle c \rangle + c'' \]

- **Q1: Outward interactions**
  - \( u'' > 0, w'' > 0 \)
  - \( c' > 0, w' > 0 \)

- **Q2: Ejections**
  - \( u'' < 0, w'' > 0 \)
  - \( c' < 0, w' > 0 \)

- **Q3: Inward interactions**
  - \( u'' < 0, w'' < 0 \)
  - \( c' < 0, w' < 0 \)

- **Q4: Sweeps**
  - \( u'' > 0, w'' < 0 \)
  - \( c' > 0, w' < 0 \)
Quadrant analysis $u'' w'', \text{ Ri} = 0$, 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
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 \( w''c'' \), \( Ri = 0.188 \)
Quadrant analysis $w'' c''$, $Ri = 0.188$

Q1/Q3

Q4 > Q1 > Q3 in magnitude

$< w'' c'' >$
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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 pollutant flux, thus reducing the pollutant dispersion from the urban canopy layer.
Acknowledgment

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