Effect of atmospheric stability on urban pollutant concentration

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ABSTRACT

The purpose of this study is to investigate and generalize the influence of atmospheric stability on pollutant concentration within urban areas. For this purpose, observation data of pollutant concentration were analyzed, and wind tunnel experiments of gas dispersion within street canyons in unstable, neutral, and stable turbulent boundary layers were conducted. It was found that normalized non-dimensional concentration $C^*$ became higher with the increase of atmospheric stability, and the ratio between $C^*$ under neutral condition and non-neutral condition was almost independent of measuring locations (flow field around measuring locations).

Keywords: urban pollutant concentration, atmospheric stability, environmental impact assessment

Introduction

For environmental impact assessment of air pollution, a Gaussian plume model is usually used in Japan. This model is applicable for pollutant dispersion from a high chimney (Fig. 1a), but it is obvious not appropriate for pollutant dispersion within an urban area (Fig. 1b). Even so, it is used for this situation in the environmental impact assessment in Japan. One of the reasons why wind tunnel experiments (WT) or Computational Fluid Dynamics (CFD) are not commonly used for environmental impact assessment for air pollution is that too many cases of wind tunnel experiments or CFD simulations would be required because various classes of atmospheric stability would have to be considered. (Eg. 16 wind directions $\times$ 10 stability classes = 160 cases). Another reason is that few institutes have a thermally stratified wind tunnel. If a general function independent of wind direction, urban shape, and location expressing the effect of atmospheric stability on pollutant concentration could be proposed, it would become possible to conduct WT/CFD for only neutral conditions and convert the results (pollutant concentrations under neutral condition) into those in other atmospheric stability conditions by using the proposed general function. We attempted to find the general function that expresses the effect of atmospheric stability on pollutant concentration from observation data and wind tunnel experiments.

![Gaussian distribution](image1.jpg)

(a) from high chimney

![Pollutant source](image2.jpg)

(b) within urban area

Figure 1  Dispersion of pollutant
Analysis of observation data

We firstly attempted to find the general function that expresses the effect of atmospheric stability on pollutant concentration by analyzing observation data at air pollution monitoring stations of the Tokyo Metropolitan Government (TMG). Observation data in this study consisted of two parts. One was hourly averaged Nitrogen oxides (NOx) concentration data observed at 25 general air pollution monitoring stations in Tokyo 23 ward area (Fig. 2). The other part was meteorological data including wind speed and direction, solar radiation and cloud cover of Japan Meteorological Agency (JMA). We downloaded these data for five years from 2006 to 2010 from the TMG website and the JMA website shown below.

- http://www.kankyo.metro.tokyo.jp/air/air_pollution/result_measurement.html

Procedure of data analysis is as follows.

Step 1. Define hourly atmospheric stability classes from 3:00 to 21:00 based on the modified Pasquill–Gifford stability [Table 1: Environmental research and control center (2000)] using above meteorological data for five years. The data from 22:00 to 2:00 were omitted because there are no cloud cover data to evaluate atmospheric stability classes during that time zone.

![Figure 2 Air pollution monitoring location in Tokyo](image)

<table>
<thead>
<tr>
<th>Surface wind speed at 10m above ground (U) (m/s)</th>
<th>T ≥ 0.6</th>
<th>0.6 &gt; T ≥ 0.3</th>
<th>0.3 &gt; T ≥ 0.15</th>
<th>T &lt; 0.15</th>
<th>8~10</th>
<th>5~7</th>
<th>0~4</th>
</tr>
</thead>
<tbody>
<tr>
<td>U &lt; 2</td>
<td>A</td>
<td>A-B</td>
<td>B</td>
<td>D</td>
<td>D</td>
<td>G</td>
<td>G</td>
</tr>
<tr>
<td>2≤ U &lt; 3</td>
<td>A-B</td>
<td>B</td>
<td>C</td>
<td>D</td>
<td>D</td>
<td>E</td>
<td>F</td>
</tr>
<tr>
<td>3≤ U &lt; 4</td>
<td>B</td>
<td>B-C</td>
<td>C</td>
<td>D</td>
<td>D</td>
<td>D</td>
<td>E</td>
</tr>
<tr>
<td>4≤ U &lt; 6</td>
<td>C</td>
<td>C-D</td>
<td>D</td>
<td>D</td>
<td>D</td>
<td>D</td>
<td>D</td>
</tr>
<tr>
<td>6 ≤ U</td>
<td>C</td>
<td>D</td>
<td>D</td>
<td>D</td>
<td>D</td>
<td>D</td>
<td>D</td>
</tr>
</tbody>
</table>

Note: The nighttime refers to the period when there is no solar radiation.
Solar radiation data are used during daytime and cloud cover data are used during nighttime.
The first and last hour of nighttime should be defined as neutral condition “D” regardless of cloud cover.

<table>
<thead>
<tr>
<th>stability class</th>
<th>A</th>
<th>A-B</th>
<th>B</th>
<th>B-C</th>
<th>C</th>
<th>C-D</th>
<th>D</th>
<th>E</th>
<th>F</th>
<th>G</th>
</tr>
</thead>
<tbody>
<tr>
<td>definition</td>
<td>very unstable</td>
<td>unstable</td>
<td>slightly unstable</td>
<td>neutral</td>
<td>slightly stable</td>
<td>stable</td>
<td>very stable</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>corresponding number</td>
<td>1</td>
<td>1.5</td>
<td>2</td>
<td>2.5</td>
<td>3</td>
<td>3.5</td>
<td>4</td>
<td>5</td>
<td>6</td>
<td>7</td>
</tr>
</tbody>
</table>
Step 2. For each station normalize hourly NO\textsubscript{x} concentration value by the formulation below.

\[ C^* = \frac{C U H}{Q} \]  

where \( C^* \) is non-dimensional normalized NO\textsubscript{x} concentration; \( C \) is observed NO\textsubscript{x} concentration (ppb); \( U \) is wind speed (m/s); \( H \) is the representative length (m) and it is always constant; \( Q \) is the emission rate (m\textsuperscript{3}/s). But in the actual procedure, only \( CU \) (ppb\cdot m/s) was calculated for \( C^* \) because \( H \) and \( Q \) can be eliminated after the following assumption and procedure.

Step 3. For each station, classify the \( C^* \) by 133 groups based on day and hour (7 days and 19 hours from 3:00 to 21:00). We assume that the NO\textsubscript{x} pollutant emission rate \( Q \) is the same if the day and hour is the same.

Step 4. For each station, divide the above 133 groups into 2128 groups (133*16) based on 16 wind directions.

Step 5. For each station, divide the above 2128 groups into 10640 groups (2128*5) based on 5 wind speed (\( U \)) ranges (0.5<\( U \)<2m/s; 2\leq\( U \)<3m/s; 3m/s\leq\( U \)<4m/s; 4m/s\leq\( U \)<6m/s; 6m/s\leq\( U \)). The first range 0.5<\( U \)<2m/s is different from the first range in table 1 (\( U \)<2m/s). We omit wind speed data less than 0.5m/s because the wind direction under very weak wind condition is not stable and always changing.

Step 6. For each station, select \( C^* \) under neutral conditions “\( C^*_{n} \)” on each day, hour, wind direction, and wind speed range.

Step 7. For each station, average the selected \( C^*_{n} \) to obtain the 5 years averaged \( C^*_{n,ave} \) values for each day, hour, wind direction, and wind speed range.

Step 8. For each station, divide all \( C^* \) data by \( C^*_{n,ave} \) to get the ratio that expresses the stability effect for each day, hour, wind direction, and wind speed range. (\( Q \) and \( H \) are eliminated in this step because the same \( Q \) and \( H \) exist in both denominator and numerator. As described in step 3, we assumed that \( Q \) is the same if the day and hour is the same. This is because industrial activities, traffic volume, and human activities in residential houses and office buildings which emit pollutants are considered to be almost the same if the day and hour is the same.)

Thus, Stability Effect Ratio = \( \frac{C^*}{C^*_{n,ave}} \)  

(2)

Fig. 3 shows an example of \( C^*_{n} \) at station No.104 for NE wind direction at each hours. 5 years averaged value of \( C^*_{n,ave} \) and \( \pm 1\sigma \) (standard deviation) are plotted in the figure. The vertical dotted lines correspond to 00:00 (midnight). The daily variation of \( C^*_{n,ave} \) in hour is regular from Mondays to Sundays. \( C^*_{n,ave} \) increases from the minimum value at 3am to the maximum value at 9:00, because 9:00 is the rush hour.

Figure 3 \( C^*_{n} \) in NE wind direction (station No.104)

We attempted to integrate all the monitoring stations data to find a general relationship between atmospheric stability and NO\textsubscript{x} concentration. The index “Stability Effect Ratio” (SER) was proposed for this purpose. It is the ratio between \( C^* \) and \( C^*_{n,ave} \) at each hour, each
day and each wind direction for each station. All averaged values of the SER ± 1σ (all stations, days, hours, wind directions, and wind speed ranges) are plotted against stability classes in Fig. 4a. The numbers in horizontal axis express the atmospheric stability classes shown in table 2. Data numbers of each class are written in the figure. The stability effect ratio (SER) is less than 1 under unstable atmospheric conditions and larger than 1 under stable atmospheric conditions. However the standard deviations are very large probably due to the variability (uncertainty) of atmospheric condition and pollutant emission rate. In order to check whether the SER in Fig. 4a is independent of urban shape and location, two additional figures are added: SER (all days, hours, wind directions, and wind speed ranges) at Station No. 104 (in Shinjuku-ku) and station No. 138 (in Edogawa-ku) were displayed in Fig. 4b and c. The tendencies of Fig. 4b-c are similar to Fig. 4a. Not only these two stations but also all the stations have the similar tendency (figures are omitted). Thus, there is a possibility that the Stability Effect Ratio (SER) is independent of urban shape and location. In addition, in order to check whether the SER in Fig. 4a is independent of wind direction, three additional figures are added (Fig. 4d-f). SER at Station No. 138 (in Edogawa-ku) under N, NE and S wind directions were shown in figures 4d-f, respectively. Some differences were found depending on wind direction. However data number is small. So we cannot judge whether the atmospheric stability ratio is independent of wind direction from these data.

Wind tunnel experiments

As mentioned above, it was found there is a possibility that the Stability Effect Ratio (SER) was independent of wind speed, urban shape and location. But the deviation of the ratio was large probably due to variability (uncertainty) of atmospheric condition and pollutant emission rate. Thus in order to reduce the variability (uncertainty) of atmospheric condition and pollutant emission rate, wind tunnel experiments were conducted in a thermally stratified wind tunnel at Tokyo Polytechnic University (TPU). Fig. 5 shows the experimental setup. The unstable, neutral, and stable turbulent boundary layers were generated by heating
or cooling wind tunnel floor and air with 23 thin roughness elements which were made of aluminum angles in the upstream. They create a long, rough upwind fetch to generate a turbulent boundary layer. Total $9 \times 14 = 126$ cubic blocks were put in the turbulent boundary layers in a downstream (Figs. 5 and 6) to represent building blocks. Each building block has the same configuration: $L \ (60\text{mm}) \times W \ (60\text{mm}) \times D \ (60\text{mm})$. The city blocks were spaced 60mm apart in both x and y direction. Tracer gas ethylene (C$_2$H$_4$) was released from a line on the floor. Fig. 7 shows measuring points. The locations of the measuring points were selected so that various flow patterns (reverse flow, upward flow, downward flow in the street canyons and flow on the roads) were included.

![Experimental setup (units: mm)](image1)

![Arrangement of building blocks](image2)

![Measuring points](image3)
Table 3 summarizes the atmospheric stability conditions. Totally 5 cases were conducted. The reference height was 0.32m, and the velocity at this height of inflow boundary was set as reference velocity \( (U_R) \). The atmospheric stability was characterized by Bulk Richardson’s number \((Ri_b)\). Bulk Richardson number is expressed as the following.

\[
Ri_b = \frac{g H_R \times (T_R - T_S)}{(T_0 + 273) \times U_R^2}
\]

Where \( g \) is the acceleration due to gravity \([m/s^2]\); \( H_R \) is the reference height \([m]\); \( T_R \) is the temperature at the reference height \([\degree C]\); \( T_S \) is the ground surface temperature \([\degree C]\); \( T_0 \) is the average inflow temperature \([\degree C]\); \( U_R \) is the velocity at the reference height \((m/s)\). The \( Ri_b \) for 5 inflow profiles were summarized in the last row of Table 1. Values of \( Ri_b \) ranged from -0.23 (unstable) to 0.29 (stable).

<table>
<thead>
<tr>
<th></th>
<th>Unstable</th>
<th>Weakly unstable</th>
<th>Neutral</th>
<th>Weakly stable</th>
<th>Stable</th>
</tr>
</thead>
<tbody>
<tr>
<td>( U_R ) (m/s)</td>
<td>1.4</td>
<td>1.8</td>
<td>1.8</td>
<td>1.5</td>
<td>1.2</td>
</tr>
<tr>
<td>( T_R ) (\degree C)</td>
<td>9</td>
<td>10</td>
<td>11</td>
<td>48</td>
<td>55</td>
</tr>
<tr>
<td>( T_S ) (\degree C)</td>
<td>49</td>
<td>41</td>
<td>11</td>
<td>16</td>
<td>14</td>
</tr>
<tr>
<td>( \Delta T ) (\degree C)</td>
<td>40</td>
<td>31</td>
<td>0</td>
<td>32</td>
<td>41</td>
</tr>
<tr>
<td>( T_0 ) (\degree C)</td>
<td>13</td>
<td>14</td>
<td>11</td>
<td>48</td>
<td>55</td>
</tr>
<tr>
<td>( Ri_b )</td>
<td>-0.23</td>
<td>-0.1</td>
<td>0</td>
<td>0.13</td>
<td>0.29</td>
</tr>
</tbody>
</table>

**Results of wind tunnel experiments**

The correlations for normalized non-dimensional concentration \( C^* \) between neutral condition and non-neutral conditions were investigated and shown in Fig. 8. The non-dimensional concentration \( C^* \) is defined as follows.

\[
C^* = \frac{C \cdot U_R \cdot H_R^2}{q}
\]

Where \( C \) is the measured concentration [-]; \( q \) is the gas emission rate \([m^3/s]\).

All the measured concentration data (measuring positions, see Fig.7) in the wind tunnel tests were included in the figures. There were totally 92 measuring points for each case. Those measuring positions located in different places. Some were in the street while some were in the canyon between blocks. In addition, four heights in vertical direction were included. As shown in the figures, data were plotted almost on a single straight line. Thus the ratio between \( C^* \) under non-neutral conditions and neutral condition were almost independent of the measurement locations (the flow filed around the measuring positions). The slope became steeper with the increase of the Bulk Richardson Number, which means non-dimensional concentration became higher with the increase of the Bulk Richardson number.

Fig. 9 shows the ratio between \( C^* \) under non-neutral condition and \( C^*_n \) under neutral condition obtained from the experimental results. This is the Stability Effect Ratio (SER) on pollutant concentration (SER= \( C^*/ C^*_n \)). Averaged SER \pm \sigma \) (the standard deviation) of all the
measuring points are plotted in the figures. As shown in the figures, with the increase of $Ri_b$, the SER increases. Since the standard deviation is relatively small, the SER is almost independent of the locations or flow fields.

![Figure 8 Correlations of $C^*$ (Neutral VS. non-neutral)](image)

**Figure 8 Correlations of $C^*$ (Neutral VS. non-neutral)**

**Figure 9 Stability Effect Ratio (SER= $C^*/C^*_n$)**

**Conclusions**

Five year’s observation data of pollutant concentration were analyzed, and wind tunnel experiments were conducted for investigating the effect of atmospheric stability on urban pollutant concentration. It was found that the Stability Effect Ratio (SER) on pollutant concentration (SER= $C^*/C^*_n$) became higher with the increase of atmospheric stability, and it was almost independent of the locations or flow fields. If the function of the SER is universal one, we can predict pollutant concentration under non-neutral condition from experimental or CFD results under neutral condition by using this function. It will bring about a drastic change
in the environmental impact assessment of air pollution in Japan. We will continue further investigation to confirm the generality of the SER function by changing urban configurations in wind tunnel experiments.

References

