Why Is Megacity Delhi Prone To High Atmospheric Pollution Potential?

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Introduction

• Delhi is amongst one of the highly polluted megacities of the world

• Ambient levels of pollutants such as NO$_2$ and Respirable Suspended Particulate Matter and Fine Particulate Matter often exceed the standard limits.

• High pollution of this nature occurs normally as a consequence of either high emissions or poor dispersion or both.
Background of the study

• Thus, it is obvious that both emissions and dispersion conditions determine the ambient concentration of a pollutant.

• Given that emission features may not change significantly over a reasonable time frame, the meteorology and climatology can play a dominant role in altering pollution potential of a city. The meteorological parameters that can be related primarily with the transport of pollutants are expected to play a major role.
Wind Velocity is the best representation of transport phenomenon and to a great extent of the diffusion as well.

Time series of observed wind velocity is normally measured at very low averaging time interval. Broadly speaking, this can be used as an indicator of the pollution potential.

It is assumed here that impact of other meteorological parameters is relatively less or mainly driven by the wind velocity and flow conditions can suitably represent these.

Also, the urban pollution being dominated more by the GL sources the wind velocity can be considered a key parameter and a reasonably representative parameter to assess the dispersion characteristics.
Objective of the study

• In this study, Special types of flow conditions such as Stagnation, recirculation and ventilation are studied to understand likely impact of wind flow on pollution potential.

• Further, an attempt is made to correlate the high levels of concentration of air pollutants such as Nitrogen dioxide, Sulfur dioxide and Particulate matter etc. with the stagnation, recirculation and ventilation characteristics.

• Emission trends of major greenhouse gases in the city has also been studied considering that these emissions will have a significant impact on the climate change given the prevailing dispersion characteristics.
The study area of Delhi

- The capital city of Delhi is located at latitude 28° 38' 17" N and longitude 77° 15' 51" E with an altitude of 215 m above sea level.

- With a population of about 13.85 million*, it is one of the rapidly growing megacities in the world.

- The city has three distinct seasons namely summer, monsoon and winter. The summer season (Apr–Jun) is governed by high temperature and hot, high speed winds. While the monsoon (Jul-Sep) is dominated by rains. The winter period (Nov- Jan) is dominated by cold, dry air and ground-based inversion with low wind conditions.

*Directorate of Economics and Statistics, Statistical Handbook of Delhi, 2006
Data Sources

• The data used in the study is for a period of about six months i.e. from December 2007 to May 2008.

• This period can be considered to span over three seasons: Winter (Dec-Jan), Spring (Feb-Mar) and Summer (Apr-May)

• WatchDog Weather Station (Model 550) was installed at Indian Institute of Technology (IIT), Delhi and 1-hour average data for wind speed and direction has been obtained from the same.
Data Sources (contd.)

• Measurement of particulate matter concentration was carried out through GRIMM Aerosol Spectrometer (Model 1.108) installed at IIT Delhi. This can measure particulate matter in 15 sizes starting 0.3 micron to more than 10 micron capable of giving minute-to-minute concentrations.

• 24-hour average data for SO$_2$ and NO$_2$ concentrations was collected from Sirifort monitoring station of Central Pollution Control Board which is the regulatory authority in the state and is close to IIT (~ 2 km).
Figure 1: The Study Area of Delhi
Definitions

- Flow conditions used here are: Stagnation, recirculation and ventilation are terms that indicate special types of flow conditions that have important consequences for the dispersion of air pollutants.

- Stagnations are events where atmospheric flows decrease in speed, or stop altogether, allowing pollutants to build up in stagnant air in the vicinity of the pollutant sources.
Definitions (contd..)

- Recirculations are events in which polluted air is initially carried away from the source but later returns to produce a high pollution episode.

- Ventilations are events in which polluted air is replaced or diluted by fresh air.

- Thus an urban airshed prone to stagnation and recirculation events has high potential for elevated pollutant concentration levels.
Methodology

• Wind Vectors of speed $U_i$ and direction $D_i$ are resolved into north-south (positive toward north) and east-west (positive toward east) components which results in a series of horizontal wind vectors:

$$n_i = U_i \cos (D_i - 180)$$

$$e_i = U_i \sin (D_i - 180)$$

• The magnitude of vector is given as

$$|\vec{V_i}| = U_i = \sqrt{n_i^2 + e_i^2}$$
Methodology (contd.)

- Set of integral quantities is defined as follows

\[
S_i = T \sum_{j=i}^{i+p} |\vec{V}_j| \quad \text{wind run}
\]

\[
X_i = T \sum_{j=i}^{i+p} n_j \quad \text{north-south transport distance}
\]

\[
Y_i = T \sum_{j=i}^{i+p} e_j \quad \text{east-west transport distance}
\]

\[
L_i = \sqrt{X_i^2 + Y_i^2} \quad \text{resultant transport distance}
\]

\[
R_i = 1 - \frac{L_i}{S_i}, \quad (0 \leq R \leq 1) \quad \text{recirculation factor}
\]

where

- \( i = 1, \ldots, N - p \)
- \( p = \tau/T - 1, \quad 0 \leq p < N, \quad [T \leq \tau < NT] \)

where \( T \) is the averaging interval of data and \( \tau \) is the desired transport time
Methodology (contd..)

- The recirculation factor $R$ gives an indication of the presence of local recirculations on time scales comparable with $\tau$.
  
  - When $R$ is equal to 0, straight-line transport has occurred with no recirculation;
  
  - when $R$ is equal to 1, zero net transport has occurred over the time interval $\tau$, and there has been a complete recirculation where the air parcel has returned to its origin.
Methodology (contd..)

• The wind run is used as a measure of stagnation;
  – a value of $S$ equal to 0 is the theoretical value defining total stagnation, that is, no winds and thus no transport.

• Ventilation is characterized by low values of $R$ and high values of $S$.

• This approach of classifying the atmosphere of different sites, for comparing the mean values of the wind run $S$ and of the recirculation factor $R$, with predetermined critical values was proposed by Allwine and Whiteman, 1993.
• The values of indices to define flow conditions are:

- \( S \leq S_c \): site prone to stagnation \( (S_c = 170 \text{ km}) \)
- \( R \geq R_c \): site prone to recirculation \( (R_c = 0.4) \)
- \( S \geq S_{cv} \) and \( R \leq R_{cv} \): site prone to ventilation

where \( S_c \) and \( R_c \) are the average daily pre determined critical transport indices (CTIs) for stagnation and recirculation, respectively, and \( S_{cv} \) and \( R_{cv} \) are the average daily CTIs for ventilation.
• Allwine and Whiteman proposed daily CTIs as $S_c = 170$ km, $R_c = 0.4$, $S_{cv} = 250$ km, and $R_{cv} = 0.2$

• These CTIs values have been used in various subsequent similar studies.*

*(Venegas and Mazzeo, 1999; Kim et al, 2007; Nankar et al, 2009)*
• In this study, Wind run (S) and recirculation factors (R) were calculated for a 24-h transport time using six months of hourly surface measurements of wind speed and direction.

• Figures 2 (a) and (b) display the results in form of percentage occurrence of stagnation and recirculation events.

• It should be noted that the calculated values for wind run and recirculation factor did not satisfy the condition for ventilation on any day.
• Mostly, the wind speed and direction scenario in Delhi leads to stagnation conditions and recirculation conditions at some times.

• Figure 3 gives seasonal wind roses of the study period. Overall, about 43% of total winds in the entire study period were observed to be under calm conditions. The highest speed was upto 3.6 ms\(^{-1}\). However, maximum wind speeds (52%) were under the range of 0.5 - 2.1 ms\(^{-1}\).

• Prevalence of calm conditions and low wind speeds supports the dominance of stagnation conditions in Delhi.
Monthly variation of percent occurrence of stagnation and recirculation events

<table>
<thead>
<tr>
<th>Month</th>
<th>Stagnation</th>
<th>Recirculation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dec-07</td>
<td>96</td>
<td>0</td>
</tr>
<tr>
<td>Jan-08</td>
<td>68</td>
<td>32</td>
</tr>
<tr>
<td>Feb-08</td>
<td>97</td>
<td>3</td>
</tr>
<tr>
<td>Mar-08</td>
<td>87</td>
<td>13</td>
</tr>
<tr>
<td>Apr-08</td>
<td>82</td>
<td>18</td>
</tr>
<tr>
<td>May-08</td>
<td>59</td>
<td>41</td>
</tr>
</tbody>
</table>

Winter: Dec-Jan; Spring: Feb-Mar; Summer: Apr-May

Seasonal variation of percent occurrence of stagnation and recirculation events

<table>
<thead>
<tr>
<th>Season</th>
<th>Stagnation</th>
<th>Recirculation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Winter</td>
<td>81</td>
<td>17</td>
</tr>
<tr>
<td>Spring</td>
<td>92</td>
<td>8</td>
</tr>
<tr>
<td>Summer</td>
<td>71</td>
<td>29</td>
</tr>
</tbody>
</table>
Figure 3: Wind Roses for Experimental Period
Effect on Ambient Air Pollution

• It was needed to determine whether the ventilation and recirculation statistics are related to ambient air pollution trends in some ways.

• For this, the wind run and recirculation factor were compared with daily average of ambient levels of NO\textsubscript{2}, SO\textsubscript{2} and PM\textsubscript{10}.

**WIND RUN**

• Figures 4(a) – (c) display the time series of wind run with these pollutants while Figure 5 shows the scatter plots of wind run vs NO\textsubscript{2}, SO\textsubscript{2} and PM\textsubscript{10}. 
Effect on Ambient Air Pollution (contd..)

• SO$_2$ concentrations are always under prescribed standard of 80 $\mu$gm$^{-3}$ for residential areas. There were higher cases of exceedence of standards in case of NO$_2$ (80) while PM$_{10}$ levels (100) mostly remain above standards.

• It can be seen that largely, there exists a negative relationship between pollutant level and wind run. Lower wind run indicates stagnation conditions which is associated with higher concentrations.

• Most negative correlation between pollutant concentration level and wind run was observed for NO$_2$ followed by PM$_{10}$ and SO$_2$. 
Effect on Ambient Air Pollution (contd.)

Recirculation Factor

• Both time series and scatter plots reveal that the relationship between ambient levels of pollutants and recirculation factor is not so well defined.

• This may be due to lower prevalence of recirculation conditions in Delhi. There is no significant recirculation of pollutants and thus recirculation factor and ambient concentration levels are not related. Recirculation does not necessarily means low wind.

• Figures 6(a) – (c) display the time series of recirculation factor with NO$_2$, SO$_2$ and PM$_{10}$ and figure 7 shows the scatter plots of recirculation factor vs these pollutants.
Figure 4 (a)

Wind Run and Ambient NO$_2$ Levels
Dec 2007 - May 2008

- Ambient 24 hour NO$_2$ Standard
- Ambient NO$_2$ Concentration
- Wind Run
- Sc = 170 km
Figure 4 (b)  
Wind Run and Ambient SO$_2$ Levels  
Dec 2007 - May 2008

- Ambient SO$_2$ Concentration, 24 Hour standard = 80 ug/m$^3$  
- Wind Run  
- Sc = 170 km

Ambient SO$_2$ Concentration (ug/m$^3$) vs Day

Wind Run (km) vs Day
Figure 4 (c) Wind Run and Ambient PM$_{10}$ Levels
Dec 2007 - May 2008

- PM-10
- 24 Hour Ambient Standard for PM10
- Wind Run
- Sc = 170 km

Ambient PM$_{10}$ Concentration (µg/m$^3$)

Day

Wind Run (km)
Figure 5: Scatter Plots of Wind Run and Pollutant Concentrations

NO$_2$  
SO$_2$  
PM$_{10}$
Figure 6 (a) Recirculation Factor and Ambient NO$_2$ Levels

Dec 2007 - May 2008

- Ambient NO$_2$ Concentration
- Recirculation Factor
- 24-Hour Ambient Standard for NO$_2$
- $R_c$

Ambient NO$_2$ Concentration (µg/m$^3$)

Day
Figure 6 (b) Recirculation Factor and Ambient SO$_2$ Levels
Dec 2007 - May 2008

Ambient SO$_2$ Concentration; 24 Hour Standard = 80 µg m$^{-3}$

Recirculation Factor $R_c = 0.4$
Figure 6 (c)  Recirculation Factor and Ambient PM$_{10}$ Levels
Dec 2007 - May 2008

Ambient PM$_{10}$ Concentration (µg/m$^3$)

Recirculation Factor

PM-10  •  24 Hour Ambient Standard for PM10  •  Recirculation Factor  •  Rc = 0.4

Day

Mohan et. al, IIT INDIA
Figure 7: Scatter Plots of Recirculation Factor and Pollutant Concentrations

NO\textsubscript{2} Concentrations

SO\textsubscript{2} Concentrations

PM\textsubscript{10} Concentrations
Greenhouse Gas Emissions

- Greenhouse gases such as CO$_2$, CH$_4$, N$_2$O etc. are key components of the global warming.

- There is a significant increase of these due to anthropogenic emissions in megacities.

- Megacities covers a large proportion of urban population and thus also become hotspots of these emissions.
Figure 8: \( \text{CO}_2 \) Emissions of Indian and other megacities of world. [Source: REAS Emission Inventory, IGES]
• Figure 9 and Table 1 show increase in emissions of major greenhouse gases in Delhi from 1990 – 2000.

• CO₂ is the major contributor towards total greenhouse gas emissions. However, CH₄ also plays a significant role in warming effect due to higher GWP.

• Thus even though increase in CH₄ emissions may be less, its potential towards increasing ambient temperatures in Delhi may be considered to be comparable.
Figure 9: Emission Trends of Major Greenhouse Gases in Delhi (1990-2000)

All emission values are in Gigagrams  

Source: Gurjar et al, 2004
Table 1: Emission change of major greenhouse gases in Delhi from 1990 – 2000

*NMVOC: Benzene, Ethylbenzene, mp-Xylene, o-Xylene, Toluene
NMVOCs are mainly precursor gases and hence do not have well defined GWP's

★GWP over 20 years
Conclusions

• A significant proportion (43 %) of wind velocities are calm conditions with almost 52 % of wind speeds below 2.1 ms$^{-1}$.

• There is strong dominance of stagnation conditions (more than 90%) in Delhi indicating poor dispersion of pollutants emitted in the city.

• Ventilation conditions are virtually non existent in Delhi. Recirculation events were also reported in only a few cases.
Conclusions (contd..)

- Wind Run, which determines the prevalence of stagnation conditions, has a significant negative relationship with concentration levels of all pollutants which were studied i.e. NO$_2$, SO$_2$, PM$_{10}$ implying that low wind run or stagnant conditions demonstrate higher pollution levels.

- However, recirculation factor was not found to have any significant relationship with any of the pollutant.
Conclusions (contd.)

- Lower correlation during recirculation conditions mainly indicate that transport of pollutants outside of city can not be ruled out as sources of pollution are spread all over the city.

- CO₂ is the major greenhouse gas in Delhi followed by CH₄. However, due to higher global warming potential, contribution of CH₄ towards warming effect in the city is comparable to that of CO₂.

- Higher pollution potential in the city may also lead to increase in greenhouse gases and subsequently aggravate climatic impact.
Thank You!