Delhi, India:

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Delhi, the capital city of India, is gearing up to host the Commonwealth Games in October 2010 (CWG 2010). With the Games around the corner, the debate on air quality in Delhi and athletes health during the Games is slowly taking center stage, very similar to the debates on air quality in Beijing before and during the Olympics Games 2008[1].

Air Pollution in Delhi

In March, 2009, the central pollution control board (CPCB) declared that the city of Delhi was "India's Asthma capital"[2]. As a rapidly expanding city, transportation, energy generation, construction, domestic burning, and industrial activity are contributing to the increasing air pollution and its resulting health and respiratory impacts. **Figure 1** presents the summary of measured PM_{10} and NO_x concentrations from the four monitoring stations in Delhi[3].

The National Capital Region (NCR) of Delhi has grown rapidly in the past two decades. It now covers an estimated area of 900 Sq. km that includes new townships and satellite centers such as Noida and Gurgaon (See the graphical representations in the Annex). In 2007, the population of NCR was estimated at 16 million. It is expected to reach 22.5 million in 2025[4].

A summary of the PM and Ozone pollution observed at one of the continuous air monitoring stations (located at the Income Tax Office - ITO) in Delhi[5] is presented in **Figure 2**. On an average, the PM pollution is 2-3 times higher than the daily ambient standard and for Ozone the daily averages remains lower than the standard, except for the day time 8-hr maxima (plotted as thick blue line) which exceed the compliance levels. Over the past decade, the government has introduced some green initiatives to address the air

[1] In case of Beijing, some stringent regulations and policy measures were implemented, months in advance, to ensure clean air days before and during the Olympic Games. However, this remains a challenge for the Delhi authorities.

[2] "Delhi is India's Asthma capital", March 1st, 2009, In Today News @ http://www.intoday.in/index.php?id=24240&option=com_content&task=view&sectionid=5
"The pollution story In Black And Pink", July 15th, 1999, Down to Earth @ http://www.downtoearth.org.in/full6.asp?foldername=19990715&filename=spr&sec_id=6&sid=4

[3] The measurement data of daily averages for the period of 2004-2007 are obtained from CPCB (Delhi, India). For the four year period, the collection efficiency at each of the stations is ~25 percent (~2-6 points per month) @ http://cpcb.nic.in
Real time monitoring data for Delhi @ http://164.100.43.188/cpcbnew/movie.html

[4] UN HABITAT, 2008, "State of the World Cities" @ http://www.unhabitat.org/content.asp?cid=5964&catid=7&typeid=46&subMenuId=0

[5] Data is collected for the period of 2006-09 for the ITO station, operated by CPCB, India, covering a range of pollutants, including meteorology @ http://164.100.43.188/cpcbnew/movie.html

pollution problem in the city. Yet, there still remains a tremendous amount of potential to reduce the air pollution impacts as the demand rises for infrastructure and services.

Pollution Sources

No single sector is responsible for Delhi's air pollution. Rather, it is a combination of factors including industries, power plants, domestic combustion of coal and biomass, and transport (direct vehicle exhaust and indirect road dust) that contribute to air pollution[6]. Seasonal changes in demand for fuel and natural pollution result in differing sources of air pollution in summer and winter. These need to be taken into account to maximize the effectiveness of anti-pollution initiatives. **Figure 3** presents the results of source apportionment of the urban air pollution in Delhi, conducted by the Georgia Tech University (USA) in 2005[7].

In summer, dust storms from the desert[8], south-west of Delhi contribute to the increased fugitive dust in the city. This is exacerbated by the low moisture content in the air, leading to higher resuspension of road dust (40 percent of particulate pollution in summer, compared to 4 percent in winter). In the winter months, the mix of pollution sources changes dramatically. The use of biomass, primarily for heating contributes to as much as 30 percent of particulate pollution in winter. Most of this burning takes place at night, when the “mixing layer height” is low due to inversion in the winter months. In summer, biomass accounts for only 9 percent of particulate pollution.

Another external factor is pollution due to agricultural clearing[9]. After the harvest of crops, clearing agricultural land is a common practice in surrounding (largely agricultural) states. The smoke reaches Delhi and contributes to the smog levels in the city[10].

Apart from biomass burning and ambient dust, transportation and industries are major contributors to air pollution in Delhi. With a growing city, the corresponding transportation needs are fueling a rise in private vehicles (2 and 4 wheelers) and taxis and autorickshaws[11].

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[6] Garg et al., 2006, “The sectoral trends of multigas emissions inventory of India”, Atmospheric Environment @ http://dx.doi.org/10.1016/j.atmosenv.2006.03.045
Gurjar et al., 2004, “Emission estimates and trends (1990–2000) for megacity Delhi and implications”, Atmospheric Environment @ http://dx.doi.org/10.1016/j.atmosenv.2004.05.057
Reddy et al., 2002, “Inventory of aerosols and sulfur dioxide emissions in India, Atmospheric Environment @ http://dx.doi.org/10.1016/S1352-2310(01)00463-0
Shah et al., 2000, “Integrated analysis of acid rain in Asia”, @ http://arjournals.annualreviews.org/doi/abs/10.1146/annurev.energy.25.1.339

[7] The source apportionment study was conducted in four Indian cities, via hydrocarbon analysis of the measured $PM_{2.5}$ samples, under the guidance of Dr. Ted Russell @ Georgia Tech University. Other cities include Chandigarh, Kolkata, and Mumbai. Please note that the source apportionment results are indicative of the possible shares of various sources in the measured sample and most often represent the surroundings of the monitoring site, instead of a directive measure for the whole city.

[8] Satellite images of forest fires, dust storms, and haze over Asia are presented @ http://urbanemissions.blogspot.com/2009/05/dust-storm-haze-pollution-in-asia.html

[9] Fires in the Northwest India, November 2008 @ http://earthobservatory.nasa.gov/NaturalHazards/view.php?id=35765

[10] BBC, November, 2008, “Pollution Fears over Delhi Smog” @ http://news.bbc.co.uk/1/hi/world/south_asia/7727114.stm

[11] Indian Express, June 17th, 2008, “Delhi Traffic at Saturation” @

As a result, operating traffic speeds have reduced for all vehicles, thus increasing idling time and pollution[12]. The largest gain in the air quality was observed at the peak of the CNG conversions for the public transport buses, taxis, and 3-wheelers in 2001-2002. And since, the air quality levels have declined gradually over the years, in the residential areas and along the major corridors.

The efforts to address this by building flyovers that connect and bypass major junctions in the city have not yielded results as expected. For one, this solution addresses only the supply side of the equation and does not influence demand management. In fact, as it becomes easier to take a private vehicle, the number of vehicles has increased (about 1000 new registrations per day in 2006[13]) thus negating many of the planned improvements. In addition, the increase in the on-street parking and encroachments by hawkers has exacerbated the situation.

Industry, the other major source – accounts for about a fifth of air pollution and includes the three power plants, at Indraprastha, Badarpur and Rajghat and ~200 brick kilns that use coal and fuel oil[14].

The growing industrial conglomerations and information technology (IT) parks, under the Special Economic Zone (SEZ) schemes[15] have also led the way in increasing the travel demand. This combined with the increasing geographic size of the cities are changing the travel patterns across the country. For example, once the satellite cities to Delhi, the NOIDA and Gurgaon have since become part of the Delhi administration, forming the National Capital Region (**Figure 4**). On a daily basis, the travel into and out of Delhi to these cities account for nearly 30-40 percent of the passenger trips[16].

With the increasing industrialized and SEZ's around the city, there is a significant change in the geographical settings, the travel behavior and the mode of transport (transformed to motorized transport) is not only increasing the vehicle kilometers traveled per day, but also exerting pressure on the limited infrastructure, leading to traffic congestion, idling, and pollution. The satellite cities are also prone to regular electricity power cuts, leading to increasing use of generator sets for local needs. This includes cinemas, hotels, hospitals, farm houses, apartment buildings, and institutions. The rapid growth has consequently led to increased fuel combustion, poor traffic management, and lack of sufficient public transport has led to deteriorating air quality, increased trip costs and substantially extended

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http://www.indianexpress.com/news/Delhi-traffic-at-saturation-level:-Report/323616/

[12] Down to Earth, May 31st, 2008, "Caravan to Disaster" @ http://www.downtoearth.org.in/full6.asp?foldername=20080531&filename=news&sec_id=9&sid=46

[13] Times of India, May 11th, 2009, "..~103,000 new passengers cars registered in India in April 2009" @ http://timesofindia.indiatimes.com/Car-sales-up-420-bikes-jump-1211-in-April/articleshow/4508229.cms

[14] White paper on pollution in Delhi, by Govt. of India @ http://envfor.nic.in/divisions/cpoll/delpolln.html

[15] India Together, 2005 @ http://www.indiatogether.org/2005/aug/eco-sezone.htm

[16] Central Road Research Institute, Delhi, India @ http://www.crridom.gov.in

the commuting times[17] resulting in longer exposure times to increasing pollution and health impacts.

Seasonality in Pollution

The diurnal and seasonal variation of the mixing layer height is very prominent in Delhi, which effects the night time and winter time concentrations. The winter time phenomenon is of utmost importance, because it starts forming in the month of October[18], the start of the CWG 2010.

For the pollution measured at the ITO station is presented as correlations between the tracer pollutants like CO, NO, SO_2, and $PM_{2.5}$ in **Figure 5**. Note that the figure indicates measured concentrations and not the emissions, and they are only indicative of the sources. The graphs also provide a distinction between the summer (dark dots) and non-summer months, linked to the seasonal differences in the mixing layer heights.

The correlation between the $PM_{2.5}$ and CO concentrations is an indication of direct emissions, most likely transport and fresh plumes from the industrial areas to the East, given the monitoring station location and the activity levels. The CO concentrations are also sourced to the chemical conversion of VOCs via photochemistry and the fraction of the PM also originates from the chemical conversion of SO_2 and NO_x emissions. The fractional analysis of the secondary contributions is not presented in this paper.

For the NO_x emissions in the transport sector, the nitric oxide (NO) is close to 90 percent of the emissions and readily oxides to nitrogen dioxide (NO_2) in the presence of sunlight. In **Figure 5** (**top right**), again a strong correlation between NO and SO_2, indicates a direct emission source, which in this case linked to the diesel combustion, from the transportation sector and possible generator sets in the vicinity. Lower concentrations of NO in the summer months coincide with the faster oxidation to NO_2 in the sunlight. The ozone pollution is higher in the summer months and linked to the presence of VOCs (CO as a proxy in **Figure 5**, **bottom left**) and the oxidizing capacity of NO_x, details of which are described in the following section.

A snapshot of the variation in monthly tracer concentrations compared to the annual average over Delhi area for year 2008 is presented in **Figure 6(a)**. This is the result of a dispersion model simulation conducted over the Delhi area, with constant emissions from all the grid cells and varying only the meteorological conditions based on NCEP Reanalysis data.

A clear conclusion is that irrespective of the constant emissions over each month, the observed concentrations are invariably 40% to 80% higher in the winter months (November, December, and January) and 10% to 60% lower in the summer months (May, June, and

[17] See the SIM-18-2009, "Indicative Impacts of Vehicular Idling on Air Emissions" @ http://urbanemissions.info/simair/simseries.html
[18] See SIM-air working paper No. 31 – "Role of Meteorology on Urban Air Pollution Dispersion: A 20yr Analysis for Delhi, India" @ http://www.urbanemissions.info/

July) when compared to the annual average tracer concentrations for the emissions domain. The pattern is consistent over the years and the shift is primarily due to the variability in the mixing layer heights and wind speeds between the seasons (and years). During the day, similar patterns are also evident, when the mixing height is routinely lower during the night time compared to the day, irrespective of the seasons.

Mathematically, this is better illustrated in **Figure 6(b)** as a box model. By definition, the ambient concentration is defined as mass over volume. Assuming that the emissions are equally mixed in an urban environment under the mixing layer, for the same emissions, a lower mixing height means higher ambient concentrations.

Similar to the mixing layer height, the wind speed is also very relevant. **Figure 6(c)** presents a summary of the surface layer wind speeds in 2008 from ECMWF for Delhi. The higher wind speeds observed in the summer months are responsible for driving part of the pollution out of the city limits, as evident in the months of June, July, and August (**Figure 2**) when the predominantly southerly winds move the pollution more north, and thus reducing the average contribution of the local emissions. The mixing layer height, presented in **Figure 6(d)**, shows the highs in the spring and summer months for the period of 2007-2008.

It is important to note that while the modeling is conducted using the meteorology pertinent to the city area, the emissions are not. The simulations provide a better understanding of the dispersion of the air pollution in the city, the pollution patterns should be best studied using a local emissions inventory, including the contributions of emissions originating outside the city (transboundary pollution). For example, in case of Delhi, a constant traffic between Delhi and its satellite cities in the south (Gurgaon and NOIDA) is a growing emission source, along with all the industrial estates in the northeast and northwest sectors.

Back-Trajectory Analysis of Meteorological Fields Reaching Delhi

The analysis presented in the previous sections focused primarily on understanding what happens to the emissions originating in the Delhi city limits, but the question of how much is the contribution of emissions outside Delhi to the pollution experienced in Delhi is explored via the back-trajectory analysis.

The back-trajectory analysis was conducted for the year 2008 using the HYSPLIT (Hybrid Single Particle Lagrangian Integrated Trajectory) model, a web-based portal for trajectory analysis, utilizing the NCEP Reanalysis data[19] [20]. The trajectories are generated one per day and advected backwards for 24 hours to indicate the meteorological origin of the air parcel[21].

[19] HYSPLIT - Hybrid Single Particle Lagrangian Integrated Trajectory. The details of the model, instructions to generate forward and backward trajectories, and resources should be referred to
Draxler, R.R. and Rolph, G.D., 2003, via NOAA Air Resources Laboratory (ARL) website, Silver Spring, MD @ http://ready.arl.noaa.gov/HYSPLIT.php

[20] For convenience, maps from only four months are presented in this paper. Download the google earth kmz files for each month @ http://www.urbanemissions.info/simair/SIM-31-2010-Met-Impacts-on-AP.html

[21] The HYSPLIT model can be used to generate trajectories every 6 hours, since the meteorological data exists at 6 hour intervals

The source point, Delhi, India is assigned at 28.6°N latitude + 77.2°E longitude at 100m above ground level. Each line in **Figure 7** indicates a trajectory for one day.

The winter and summer months see a strong influence of northern and northeasterly winds, passing cold temperatures over the city and the resultant low mixing layer heights. The summer and late fall months experience a mix of southern winds, increasing the possibility of pollution entrainment from the southern satellite cities.

Diurnal Cycles in Pollution

In the morning and evening traffic hours, the transport sector is the predominant source of pollution at the ITO monitoring site. **Figure 8** shows typical variation of $PM_{2.5}$, Ozone, CO, SO_2, NO_x, and NO_2, over a twenty four hour period for the year 2008. The graphs indicate an average of the measured concentrations for each hour over all days in 2008.

Truck Pollution @ Night

An important observation in **Figure 8** is the diurnal variation of the $PM_{2.5}$ pollution. Besides the rush hours bumps (8-10 in the morning and 6-9 in the evening) the steady increase in the pollution levels is attributed to two reasons – a direct source from trucks, which are allowed to pass through the city after 9 PM and a change in the mixing layer height. The influence of the truck emissions is more evident in the direct correlation of the $PM_{2.5}$ cycle with the SO_2 concentrations, possibly originating from the diesel combustion in trucks.

While the passenger travel in the city has grown over the last decade[22], the importance of the freight transport (via trucks) in the night should not be neglected, since the high concentrations observed during the night tend to linger during the rush hours (mixed with the passenger travel) and beyond (through ~11 AM) and hence increasing the exposure times and related health concerns along the major corridor.

Emissions Inventory for Delhi, India

For the area, covering the NCR of Delhi, an emissions inventory to reflect the trends and sources observed in 2010 is under development, as part of the air quality forecasting program[23] for Delhi, India, including all key species – PM, SO_2, NO_x, BC, CO, and VOCs, and covering all the primary sources of emissions – transport (especially passenger travel), industrial clusters, power plants, residential fuel use for cooking and heating (including biomass), generator sets (in households, industries, cinemas, institutions, hospitals, hotels, apartment buildings, and farm houses) and garbage burning (especially where the waste collection efficiencies are small).

[22] SIM-24-2009, “Motorized Passenger Travel in Urban India: Emissions & Co-Benefits Analysis” @ http://urbanemissions.info/simair/simseries.html

[23] The “Clean Air for Delhi 2010 and beyond” project, funded by the Government of France under their FASEP bilateral funds; implemented by Aria Technologies SA and Leosphere SA (Paris, France), in technical collaboration with the Central Pollution Control Board (CPCB), Delhi, India.

The urban inventory is further segregated spatially (**Figure 9**) to allow for diurnal and geographical variations among all the sectors. For this inventory, data was collected from many sources – including surveys conducted by local agencies, such as Center for Road Research Institute on traffic density on main corridors, CPCB on the industrial clusters in NCR, and fuel usage for cooking and heating in the residential sector by the project team. The inventory presented in **Figure 9** is updated to reflect the consumption patterns in 2010.

The emissions inventory is maintained in geo-referenced system to further analyze the vulnerable areas include residential vs. industrial areas, hot spots for the monitoring the pollution, the transport corridors, venue locations and the Games Village (specific product for the 2010 CWG). The model-ready emission inventory also includes diurnal cycles for the transport sector emissions to distinguish between the rush and non-rush hours for all modes, operational hours for the industrial sector, and cooking and heating hours for the domestic sector.

Air Quality Index for Delhi

Applied Methodology

The methodology to calculate the air quality index (AQI) is presented below, along with the supporting data for various ranges (**Table 1**).

$$AQI = \frac{AQI_{hi} - AQI_{lo}}{BP_{hi} - BP_{lo}} * (CONC - BP_{lo}) + AQI_{lo}$$

Where

CONC = concentration of the pollutant
AQI = air quality index for the pollutant
BP_{hi} = the breakpoint that is greater than or equal to CONC
BP_{lo} = the breakpoint that is less than or equal to CONC
AQI_{hi} = the AQI value corresponding to BP_{hi}
AQI_{lo} = the AQI value corresponding to BP_{lo}

The break point concentrations (high and low) are adjusted to the national ambient standards of India for each of the pollutant[24]. The AQI ranges are adjusted with 150 as the threshold, corresponding to the ambient standard for that pollutant[25].

Air Quality Index Results

Using the methodology above, AQI was calculated for the period of August, 2006 to June, 2010 for two stations across Delhi. For this analysis, AQI's are calculated in 6 bins as described below (see **Table 2**). The first three bins, at par with the national ambient air

[24] National ambient air quality standards @ http://cpcb.nic.in/National_Ambient_Air_Quality_Standards.php
[25] This is not an official AQI methodology for India, but an attempt to consolidate the available information and put together a reasonable methodology.

quality standards are considered "safe mode" or "clean air" days and the others "polluted" days.

Of the six criteria pollutants – PM (coarse and fine), SO_2, NO_x, CO, and Ozone, the PM pollution is routinely above the daily average standards[26] and the conditional pollutant for calculating the AQI for health impacts assessments – presenting the worst AQI[27]. In case of Delhi, the AQI is calculated for the PM pollution only for the two stations – (1) Income Tax Office (ITO) and (2) Delhi College of Engineering (DCE), where the monitoring data is available for PM. The **Figure 10** presents estimated AQI due to $PM_{2.5}$ pollution @ ITO and estimated AQI due to PM_{10} pollution @ DCE.

Observations on AQI

- At the monitoring sites, AQI is often more than the healthy levels of 150. The ITO is a traffic junction and accounted for 19% of the days less then 100 AQI and 33% of the days less than 150. The DCE is a background station in the north and tends to measure lower than the city averages and yet struggled to stay in the green with only 24% of the days less than 150 AQI.
- In **Figure 10(a) and 10(b)**, the winter months are highlighted with a blue box for each year. The winter months experience the worst pollution in each year starting in October and leading up to the February, the following year.
- A large portion of the AQI's greater than 300 (summary presented in **Figure 10(c)**) are associated with the winter season.

What CAN Delhi?

The air quality in Delhi improved in the early 2000's due to a number of interventions, including the large scale conversion of the bus fleet and the 3 wheeler fleet from the conventional gasoline and diesel to compressed natural gas[28]. However, the large increase in the demand for personal transport and construction activities reversed the trends.

A major intervention that Delhi is banking on is the extension of the metro rail system, to shift the motorized transport trends to the metro rail system. The expected level of shift is uncertain, which depends on a number of factors. A "what-if" analysis reveals a possible reduction of ~7 percent in the criteria pollutant emissions in 2010 and ranging anywhere from 20-55 percent reduction from expanded metro rail system. This is also very consistent with the other cities like Mumbai, Shanghai, Beijing, Bangkok, and Hong Kong, which experienced significant changes in the air quality after the expansion of the public transport

[26] Daily average national ambient air quality standards for PM_{10} and $PM_{2.5}$ are 100 $\mu g/m^3$ and 60 $\mu g/m^3$, respectively. Comparatively, the national ambient standards for $PM_{2.5}$ in United States and Europe are 35 $\mu g/m^3$ and 25 $\mu g/m^3$, respectively.

[27] The AQI was also calculated for pollutants, where and when data was available. For SO2, NO2, and Ozone, the AQI remained under the 150 more for most of the times and at very few occasions crossed the 150 mark for CO. For most instances, the PM remained the conditional pollutant in calculating the AQI. Hence the decision present only PM based AQI in this analysis.

[28] A recent report on the benefits of CNG conversion are summarized in "Climate Impacts of Air Quality Policy: Switching to a Natural Gas-Fueled Public Transportation System in New Delhi", *Environmental Science and Technology*, 2008. @ http://pubs.acs.org/doi/abs/10.1021/es702863p

systems. Certainly, the challenge will be public awareness, promotions, and incentive schemes for the public to use these systems more frequently than their personal mode of transport.

In the transport sector, the emphasis is on the public transport. The JNNURM funds for buses and urban transport strategy of India are promoting the need for infrastructure for new buses (via two of the largest manufacturing firms - Tata and Ashok Leyland). A good public transport system, including substantial support for non-motorized transport (NMT), is expected to help reduce the congestion levels, energy demand, and thus emissions from the transport sector. However, the initial phase via the introduction of the Bus Rapid Transport for ~5km lane and promoting NMT along the path dealt with severe teething problems.

With the Commonwealth Games around the corner, a lesson from Beijing to Delhi is very obvious. The involved institutions need immediate focus on the local air quality in order to bring these high pollution levels to a manageable level, fast and efficiently. Some suggestions to the public bodies include

- Improve the number of air quality monitors operated in the city. There are more monitoring stations than the stations that can actually deliver monitoring data. Even if we consider the most important pollutant, such as PM and not worry about the other pollutants (in order to keep the costs low), the stations that measure this are limited.
- More than operations, the data should be made public as frequently and consistently as possible, so general public are also aware of the consequences of their actions.
- Better understand the sources, the contributions of in-city and outside-city pollution sources. Currently, a lot of emphasis is put on the transport sector. However, the contributions from the industrial, power, and residential sources are very significant and in October (and in the winter months), with low inversions, these low lying residential sources (via biomass burning) will hinder the “clean air” goal.
- The hot spots of industrial and residential areas (many of them outside the Delhi area, but included in the National Capital Region) should be better monitored to manage the emissions
- Given that the Delhi Government neither can shut down industries nor stop half their in-use vehicle fleet during the CWG 2010, unlike the Beijing Government during the Olympic Games in 2008, a series of innovative interventions could be introduced for fast and effective air quality management. Such as
    - Shut down part of the industries, depending on the meteorological and air quality forecasts (either daily and weekly)
    - Strict restrictions on garbage burning during the winter months, especially the open burning for heating purposes in the residential areas
    - One way transport along the major corridors for better flow of the traffic
    - Aggressive procurement of buses and incentives for promoting the use of bus and metro rail systems
    - Promote telecommuting where possible, especially along the NOIDA-Gurgaon sector, which experiences the largest rush hour traffic during the week days

- Promote wet sweeping of the all the major roads, at least once in two days to reduce the amount of dust loading and thus reduce the resuspension due to increasing vehicular movement

Figure 1: Daily average monitoring data four manual stations in Delhi, India

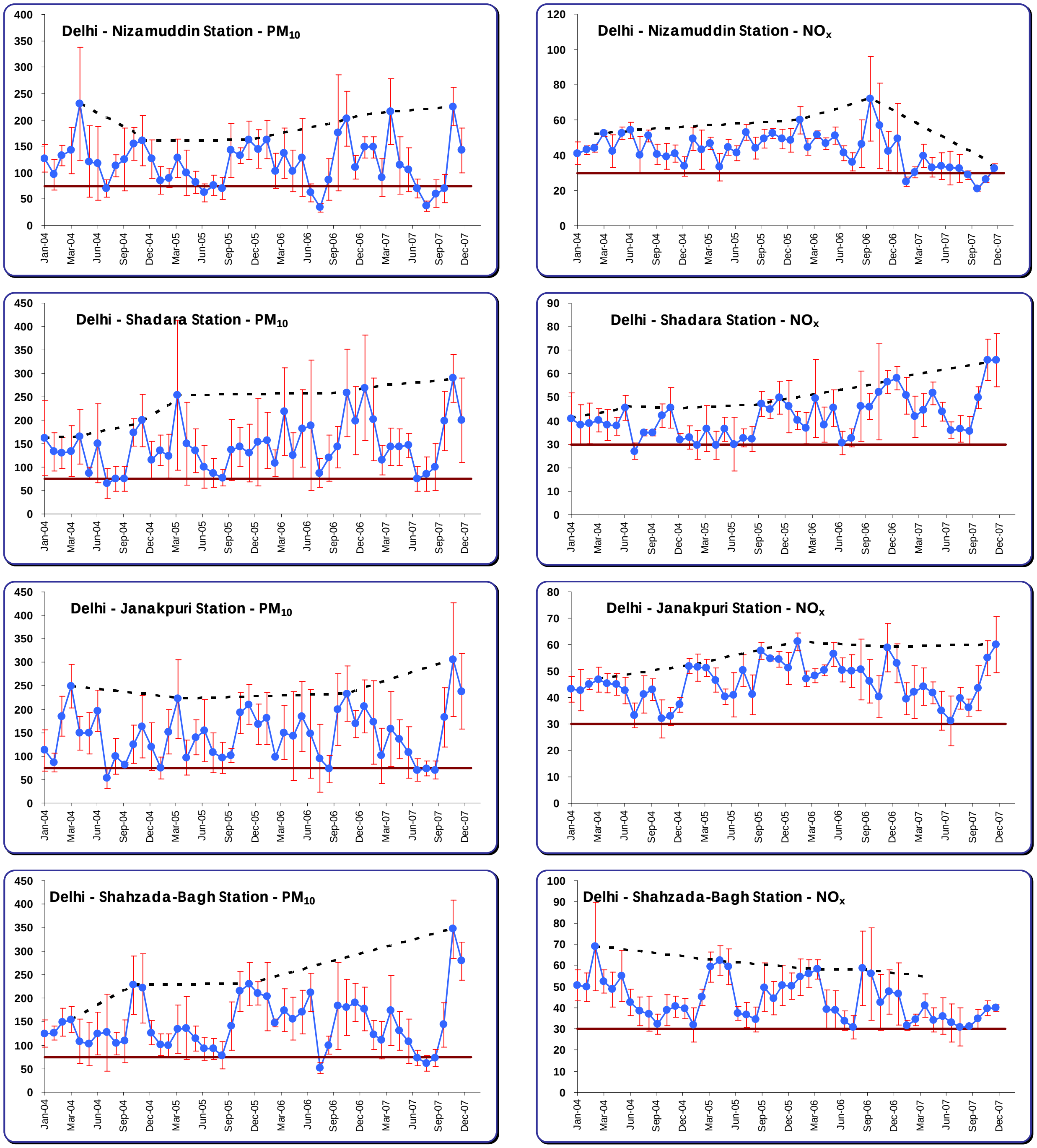

Figure 2: Daily average monitoring data at the ITO station in Delhi, India

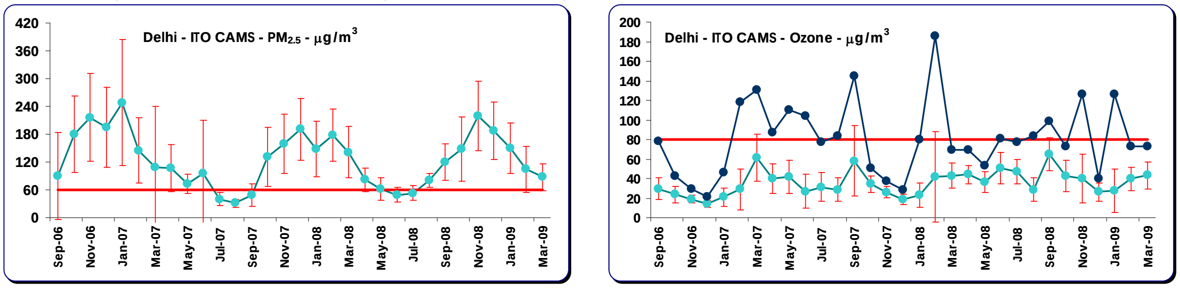

Figure 3: PM2.5 Source apportionment results for Delhi

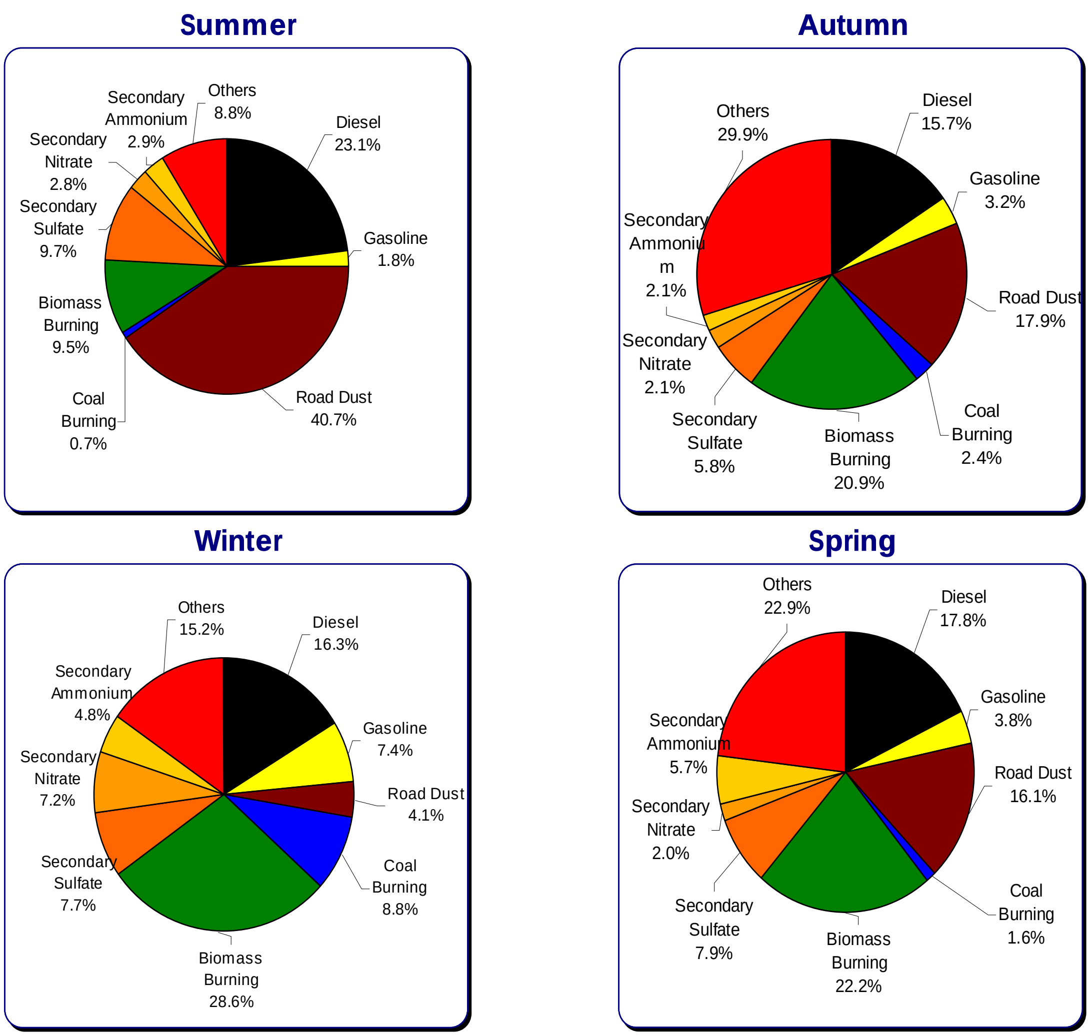

Figure 4: Travel demand from the satellite cities in Delhi, India

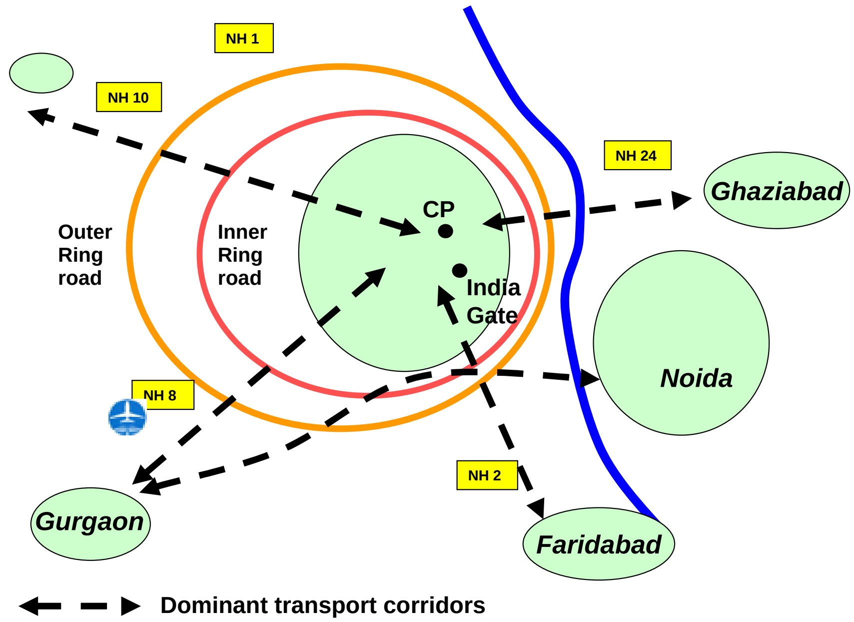

Figure 5: Correlations between criteria pollutants of measured daily averages (2006-09) at the ITO station in Delhi, India

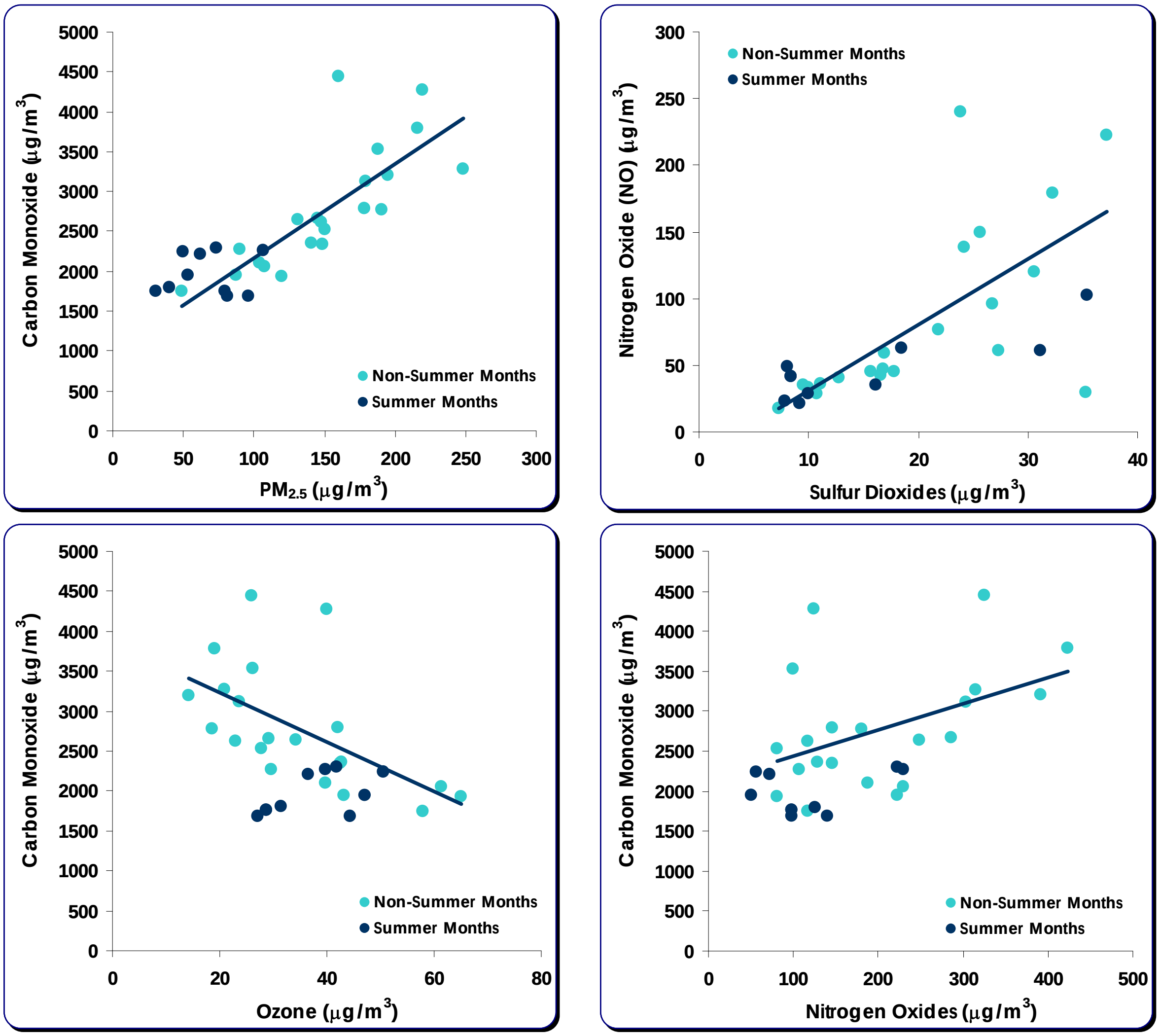

Figure 6: (a) Variation of monthly average tracer concentrations compared to the annual average concentration for the Delhi emission domain
(b) Box model illustration of the impact of the mixing layer height
(c) Figure 6: Wind Speed for Delhi domain, estimated from ECMWF
(d) Mixing layer height in Delhi, estimated from NCEP Reanalysis data

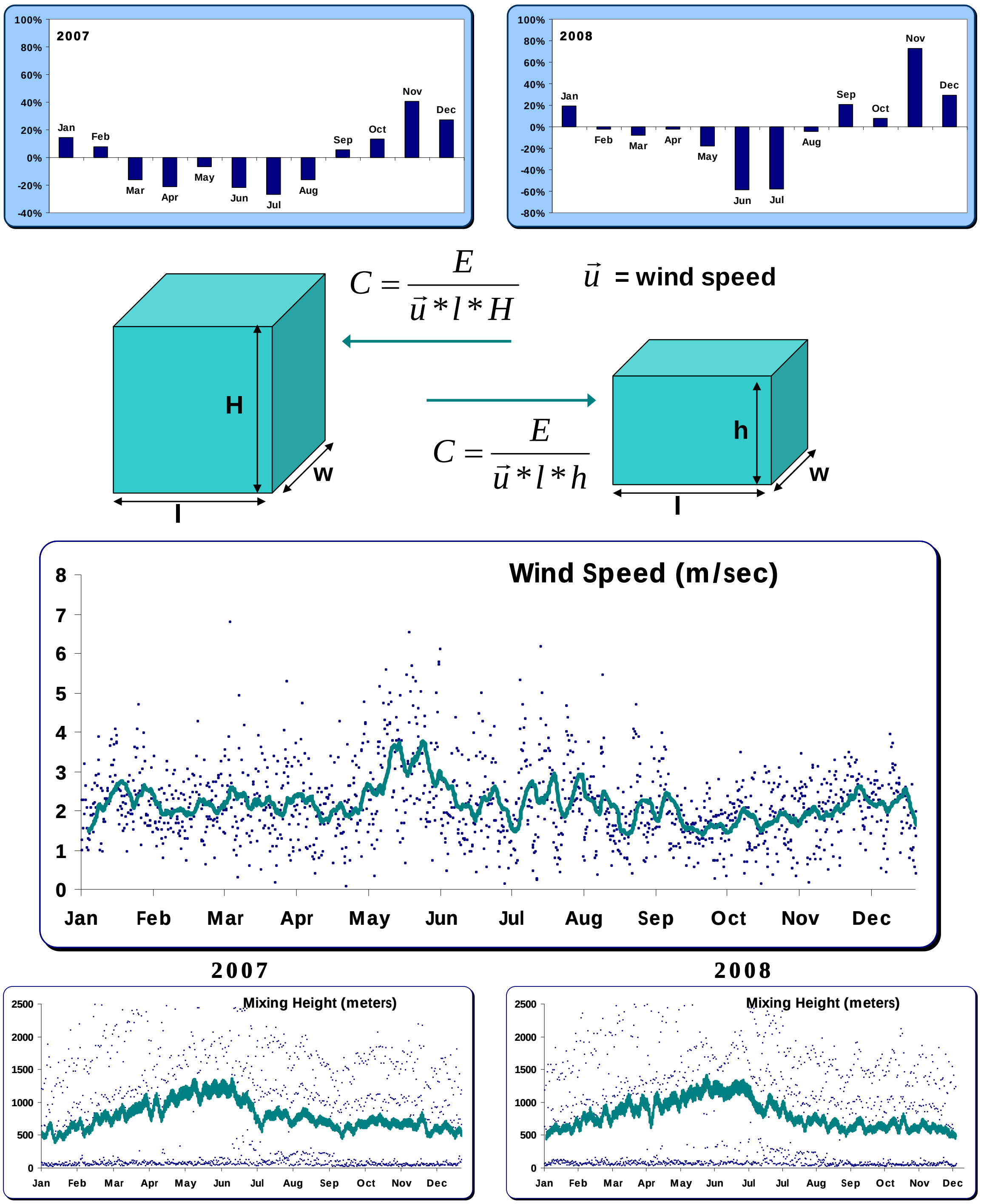

Figure 7: Back trajectories for Delhi, India for four months in 2008

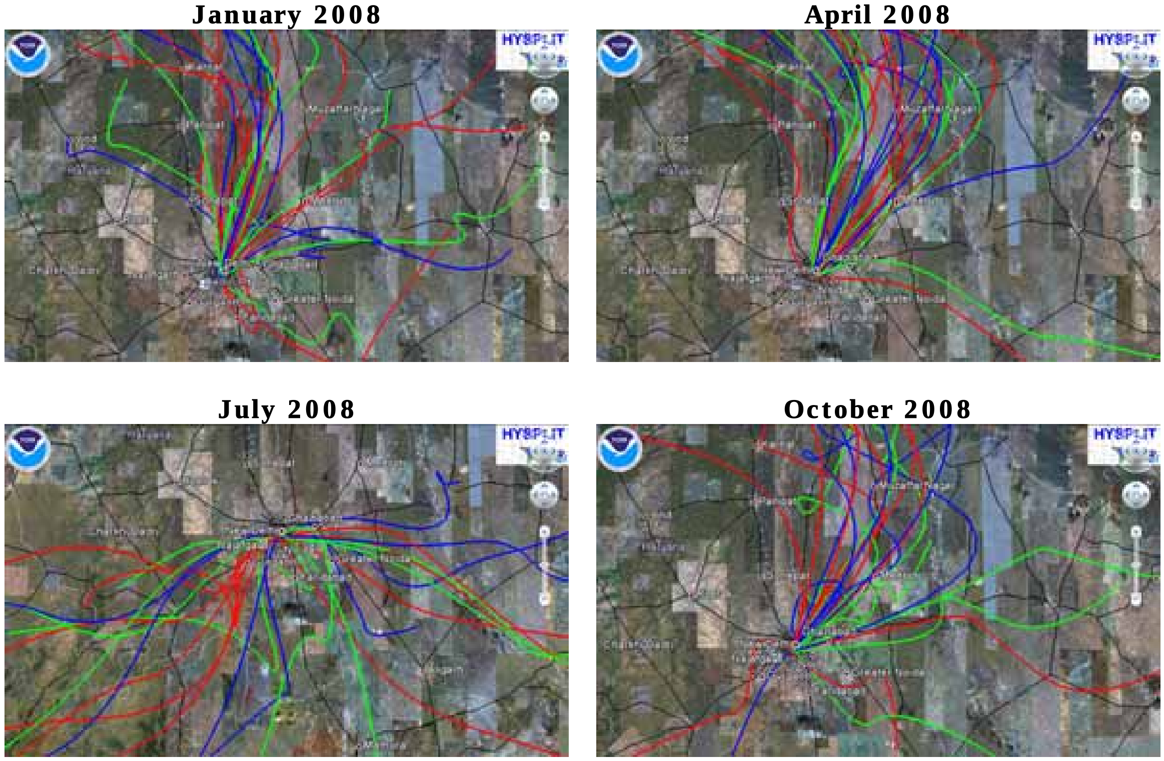

Figure 8: Diurnal variation of pollution at the ITO station in Delhi, India, averaged over all days in 2008

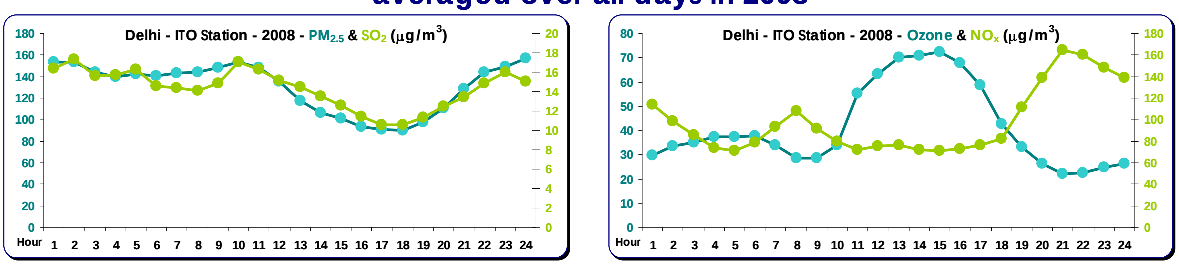

Figure 9: Distribution mechanisms utilized for urban scale emissions

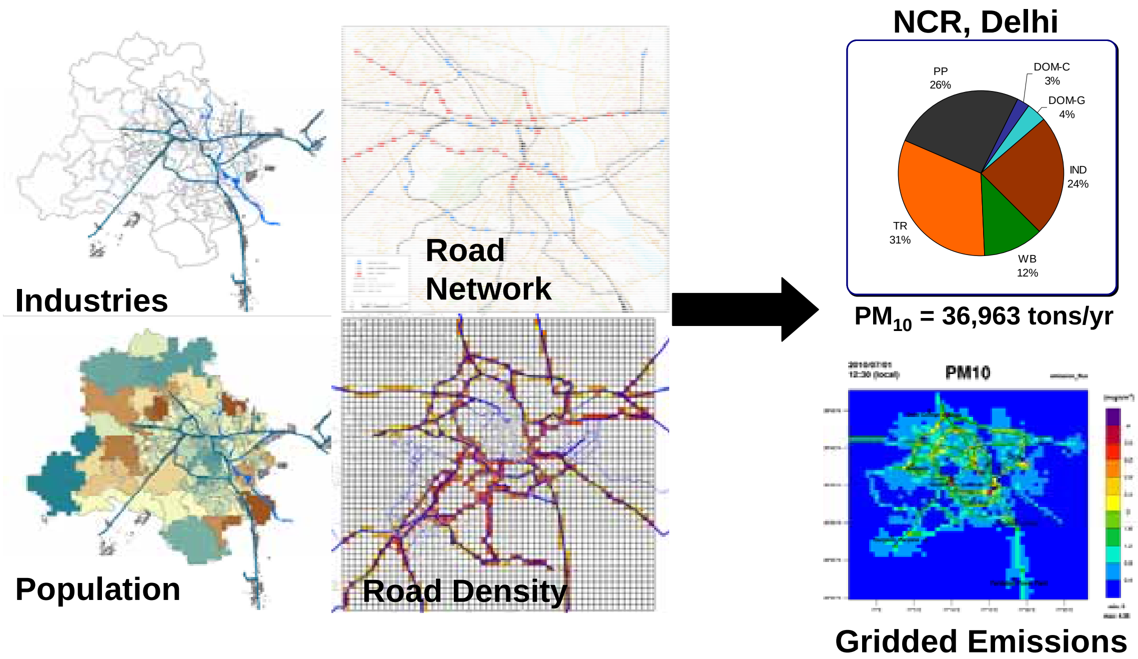

Figure 10: (a) AQI based on $PM_{2.5}$ measurements @ ITO monitoring station (b) AQI based on PM_{10} measurements @ DCE monitoring station (c) Frequency of AQI between July 2006 and August 2010

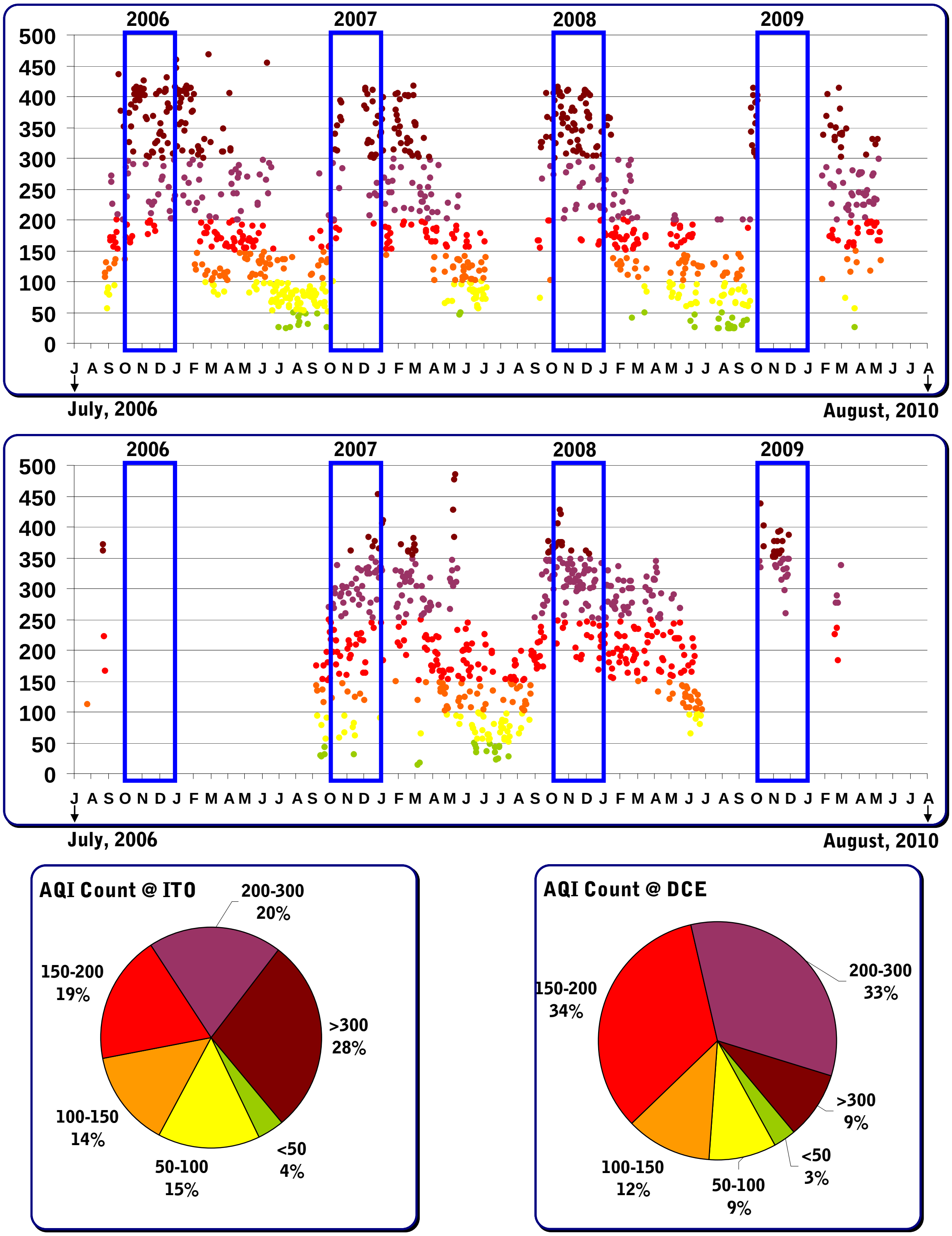

Table 1: The applicable ranges for AQI methodology for Delhi, India

Range		Healthy		Moderate		Unhealthy1		Unhealthy2		Very Unhealthy		Hazardous	
Values	AQI-low	0		51		101		151		201		301	
	AQI-hi	50		100		150		200		300		500	
Concentrations		BP_{low}	BP_{hi}	BP_{low}	BP_{hi}	BP_{low}	BP_{hi}	BP_{low}	BP_{hi}	BP_{low}	BP_{hi}	BP_{low}	BP_{hi}
PM_{10} ($\mu g/m^3$)		0	40	40	80	80	120	120	200	200	300	300	
$PM_{2.5}$ ($\mu g/m^3$)		0	25	25	50	50	70	70	100	100	150	150	
SO_2 (ppm)		0	0.01	0.01	0.02	0.02	0.04	0.04	0.10	0.01	0.15	0.15	
NO_2 (ppm)		0	0.02	0.02	0.04	0.04	0.06	0.06	0.10	0.10	0.20	0.20	
O_3 (ppm)		0	0.03	0.03	0.06	0.06	0.10	0.10	0.15	0.15	0.25	0.25	
CO (ppm)		0	2	2	7	7	12	12	15	15	30	30	