Simple Interactive Models for Better Air Quality

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Air Quality Forecasting System for Cities:
Modeling Architecture for Delhi

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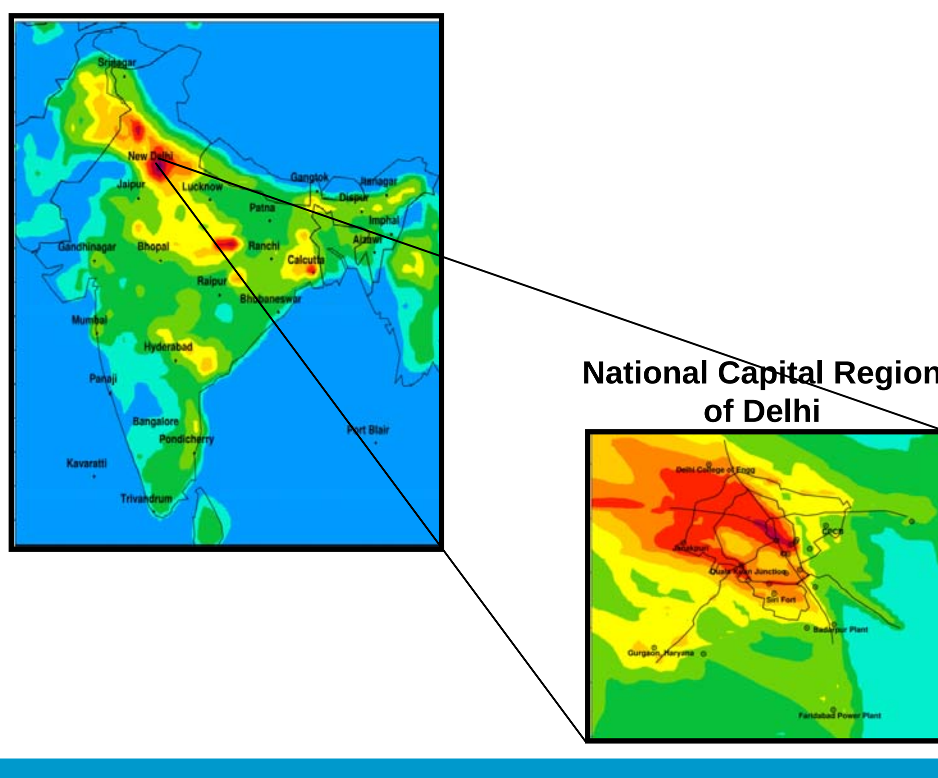

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Air Quality Forecasting System for Cities: Modeling Architecture for Delhi, India

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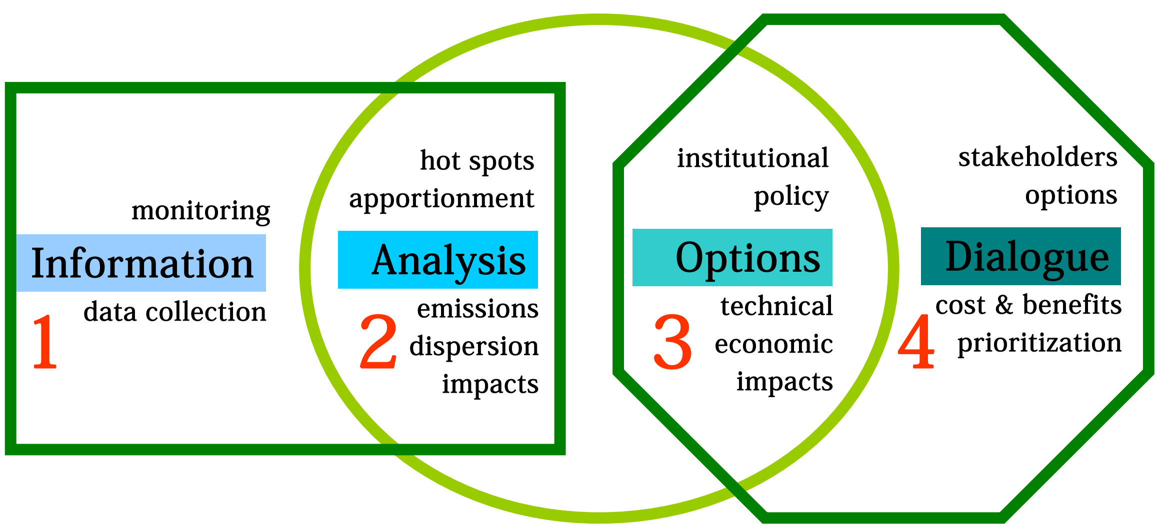
In a number of cities in India, air pollution is a growing problem, not only limited to the megacities, but also spreading through the tier II and tier III cities. Given a diverse mix of sources in these cities, with megacities dominated with transport sector and the secondary cities with industrial sectors, combined with the boom in the construction sector, use of biomass and biofuels in the residential areas, the air pollution is emerging as a complex problem and not limited to one pollutant.

The most common pollutants in question are particulate matter (PM – coarse with an aerodynamic diameter less than 10 micron meter, PM_{10}, and fine with an aerodynamic diameter less than 2.5 micron meter, $PM_{2.5}$), Sulfur Dioxide (SO_2), Nitrogen Oxides (NO_x), Volatile Organic Compounds (VOCs), Carbon Monoxide (CO), and Ozone (due to chemical reactions between NO_x and VOC species).

Four Steps that Define City's Air Quality Management Plan

Today, the integrated air quality management (AQM) is a challenging effort because of the vast information gap, especially in setting up the priority areas to support and implement an effective management plan for a city. While it is obvious that there are no cookie cutter solutions to control air pollution that fit all the cities needs, there are four steps to address the information gaps and for better results.

Figure 1: Informed decision making for air quality management



Monitoring for better air quality management

This is the easiest and first of the steps that any of the air quality institutions can undertake. The term "easiest" is relative and refers more to the ease of possible logistics involved in setting a monitoring station compared to the logistics involved in the following steps. A variety of monitors are available for all pollutants and yet there is a serious lack of scaling up this step in many cities, including the megacities. The monitoring of air pollution is crucial not only for the regulatory bodies (responsible for clean air), but also for the academic and other supporting agencies (which can help in later stages), by calibrating the models and providing necessary inputs for better air quality management.

Knowledge of pollution sources and geography of the city

This step brings together the scientific knowledge for determining pollutant emissions and regulatory aspects to formulate city's reaction to air pollution crisis. There is an acute need for pollution source apportionment, which will enable to determine the sources based on the monitoring data (and some statistical analysis) and utilize that for proper training and capacity development towards air quality management[1]. In some cases, this step is conducted in a bottom-up manner by listing the possible sources present in the vicinity of the city[2]. Also, it is important to understand the geography of the cities, which is an integral part of understanding how the emissions from various sources will interact and impact the observed air pollution patterns.

Emissions and Dispersion Modeling for Planning

Ideally, any institution concerned with pollution (and related health impacts) is expected to have (or develop) an emissions inventory for all pollutants, but due to inherent challenges in collecting the necessary data, disclosure issues with various agencies, or lack of institutional and technical capability to handle the knowledge base, leads to an incomplete or inconsistent emissions inventory. While a detailed emissions inventory is desired, it is important that an effort is put in place to start the process of establishing the same, as it takes time to establish a credible inventory - even if it means starting with averages, gross consumption levels, and borrowed emission factors[3].

As much as it is important to establish a baseline, it is also important to acknowledge the uncertainty of the inventories. If average numbers from similar experiments are used, then it should be noted and when the local capacity is developed, the inventories should be

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[1] The Ministry of Environment and Forests and Central Pollution Control Board of India has recently completed and published detailed study on source apportionment and emissions inventory (for the study domains) for six cities in India – Pune, Chennai, Bangalore, Mumbai, Kanpur, and Delhi. The study was conducted for the base year 2006-07 providing the necessary backgrounds for further action plans and studies in these cities. Detailed report is available @ http://cpcb.nic.in/Source_Apportionment_Studies.php

A source apportionment and co-benefits of air pollution management for Hyderabad was conducted and published in 2007-08 @ http://urbanemissions.info/model-tools/sim-air/hyderabad-india.html

[2] A review of the source apportionment and emissions inventory methods utilized across the world is available @ http://urbanemissions.info/publications/other-publications/source-apportionment.html

[3] Resources to average emission factors for vehicular emissions inventory development @ http://urbanemissions.blogspot.com/2009/01/average-vehicular-emission-factors.html

corrected. This is a "*learning while building*" exercise and only by establishing a baseline with what is available that one can understand what is lacking and how to improve further[4].

The importance of emissions and dispersion modeling and the effect of long range transport of various pollutants along with their possible chemical transformation are studied extensively at urban, regional, national, and inter-continental levels[5]. Similar to the emissions baseline development, the dispersion modeling is an intense exercise, which requires both computational power (nowadays, which is not a problem) and data assimilation. The modeling systems are plenty available (and free), with varying capacity and complexity to address physical and chemical aspects of atmospheric transport of pollutant. However, selection of the modeling system should be based on the objective of the program and institutional strength to absorb the analytical challenges.

Dissemination of information

While the availability of relevant data on air pollution is difficult, a growing challenge is with the dissemination of the (right) information to the policy makers and the public. As part of an integrated AQM, the combination of regulations, awareness and capacity building, and partnerships between stakeholders (including artists) contribute equally towards improving air quality in a city[6].

Need for an Air Quality Forecasting System for Cities

From **Figure 1**, an integrated AQM includes ensuring thorough and reliable monitoring of ambient concentrations as well as: keeping the authorities and the public informed about the short- and long-term changes in air quality; developing accurate emission inventories; keeping an inventory of sources of various pollutants; analyzing the dispersion of pollutants emitted from various sources; measuring the impacts of pollutant exposure on health; assessing the results of abatement measures; and thereby providing the best abatement

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[4] Examples of emissions inventories available in the public domain
Global Emissions Inventory Activity @ http://www.geiacenter.org/
Emissions Database for Global Atmospheric Research @ http://www.mnp.nl/edgar/
Greenhouse Gas and Air Pollution Interactions and Synergies @ http://gains.iiasa.ac.at/index.php
Wang et al., 2005, "Emissions inventory for Eastern China in 2000", Atmospheric Environment @ http://dx.doi.org/10.1016/j.atmosenv.2005.06.051
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
Streets et al., 2003, "An inventory of gaseous and aerosol emissions in Asia in 2000", J. of Geophysical Research @ http://www.agu.org/pubs/crossref/2003/2002JD003093.shtml

[5] Examples of Urban, Regional, and Global scale atmospheris dispersion modeling exercises
MEGAPOLI Study @ http://megapoli.dmi.dk/
Task Force for Hemispheric Transport of Air Pollution @ http://www.htap.org/
Better Air Quality for North America @ http://www.narsto.org/
European Monitoring and Evaluation Programme @ http://www.emep.int/
IIASA – GAINS Program @ http://gains.iiasa.ac.at/index.php/home-page

[6] See SIM-air working paper No.34 "AQI Methodology and Applications" for examples on how artists are using the available air quality data to raise awareness among public on a daily basis via innovative means. @ http://www.urbanemissions.info/

strategies possible within the given available resources. Such a management system is especially lacking in the developing countries.

An effective AQM, besides tools & techniques, will require reliable information on air pollution concentrations in the ambient air. This has been traditionally the challenge, especially in the developing country cities. The ambient level data can be obtained in two ways – (1) through measurement campaigns either for compliance purposes or regulatory monitoring and (2) through dispersion modeling.

The data from the first method is available with some temporal and spatial limitations, due to sampling & analytical differences, leading to gaps in information which cannot be directly used for planning long-term mitigation strategies. This data is useful for explaining the trends (diurnal and seasonal), studying the role of meteorology and chemical reactions on the mix of emissions, and auditing for compliance for limited areas.

The automatic continuous air quality monitoring systems, capable of delivering data almost in real-time basis, have gained ground compared to the traditional filter-based-high-volume-once-a-day monitoring systems, and are increasing in demand by the city authorities for information generation and usage[7].

Still, the monitoring networks are limited in number and due to operational and maintenance cost, have the limitation of not being representative of the city or the region at all times[8]. For online decision support system, real-time action planning the data from the monitoring networks has been useful, but with limited success.

Under such situations, the second method - dispersion modeling can be a very promising tool, given some baseline information for the city or the region, is capable of providing air pollution information for the entire geographical spread, for all time periods – hours, days, months, or year, either in a forecast mode for short-term alerts/planning or scenario analysis of interventions for long-term strategy.

The dispersion modeling for analyzing the "what-if" scenarios is a known science and utilized in both developed and developing countries alike. On the other hand, the air quality forecasting is fairly new and aims for public health on a day to day basis[9]. For example, the

[7] Air quality monitoring networks in Asia
@ http://urbanemissions.blogspot.com/2009/01/air-quality-monitoring-in-asian.html

[8] In India, the Central Pollution Control Board operates a monitoring network of 400+ manual stations measuring PM, SO2, and NO2, at the frequency of ~2 or 3 times a week. The data is made available at the "Environmental Data Bank (EDB) @ http://cpcbedb.nic.in/

[9] While the forecasting systems are desirable, one should note that these exercises are very data intensive and computationally challenging. There is also an incubation period where the models developed need to be calibrated and tested for better understanding the chemical behavior of the local emissions, in conjunction with the monitoring data.

forecasting systems were previously developed and are in use in the United States[10], the European Union[11], and some countries in Asia[12].

This paper presents the modeling architecture for an air quality forecasting system implemented for the city of Delhi, launched before the Commonwealth Games in October, 2010. The system for Delhi is the first in India and aims at providing information to the public, public bodies, academia, media, and private entities, on the daily air pollution for 48 hours in advance.

This system was funded by the Government of France under their FASEP bilateral funds program and developed by Aria Technologies SA and Leosphere SA (Paris, France), in technical collaboration with the Central Pollution Control Board (CPCB), Delhi, India. The two French firms were previously involved in developing similar system for Beijing, during the 2008 Olympic Games and are developing one for Rio de Janeiro for 2016 Olympic Games.

Modeling Architecture for Delhi, India

Today most of the models in use, for meteorological modeling and chemical transport dispersion modeling, are available free of cost and the challenge is mainly in configuring the systems for local specifications and having the computational power to perform the analysis on a day to day basis.

Major steps in designing an air quality forecasting system are (presented in **Figure 2**)

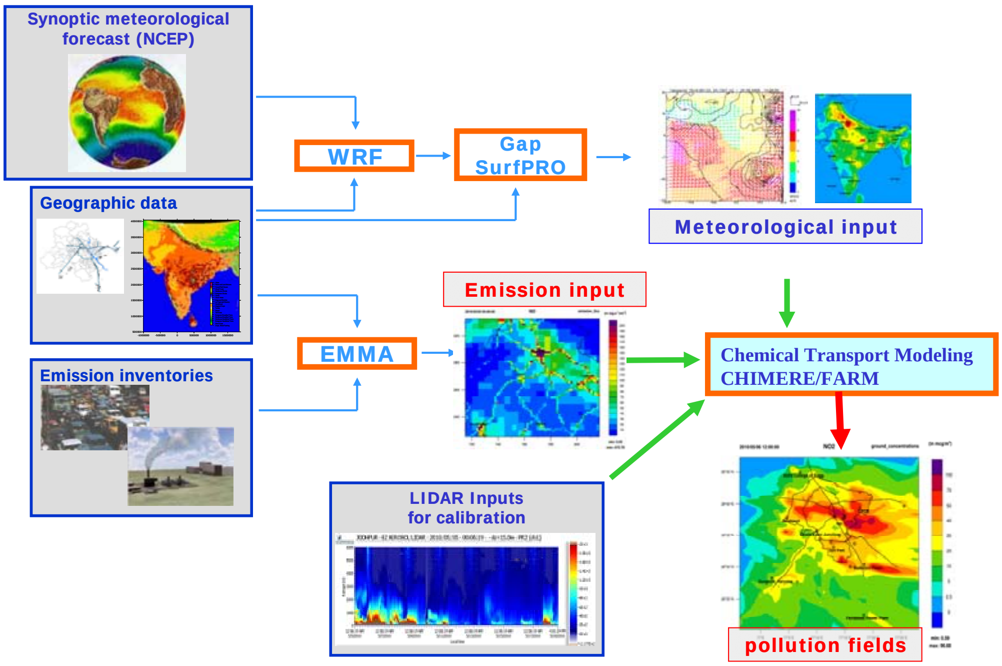
1. Domain configuration
2. Meteorological forecasting
3. Initial and boundary conditions
4. Emissions inventories
5. Chemical transport dispersion modeling
6. Calibration of the results and
7. Dissemination strategy.

The forecasting system for Delhi was built on INTEL multi-core platform with 12 CPUs (and 24 Threads) and all the modeling tools are programmed in parallel mode, optimized for faster computations, established with geo-referenced databases, interlinked with post-processing tools for web and text based outputs, and archiving procedures for prognostic

[10] The AirNow program covers the United States and Canada region providing the air pollution information by zip code for the criteria pollutants, along with the health alerts @ http://www.airnow.gov
[11] Similar to the United States, data for the European Union nations is available @ http://www.airqualitynow.eu/
[12] Some of the Asia cities have previously developed these systems and in use
Singapore @ http://app2.nea.gov.sg/psi.aspx
Bangkok, Thailand @ http://www.pcd.go.th/AirQuality/Bangkok/Default.cfm
Shandghai, China @ http://www.semc.com.cn/expoair/WebFront/default.aspx
South Korea @ http://www.airkorea.or.kr/airkorea/eng/realtime/main.jsp
Taiwan @ http://210.69.101.141/taqm/en/default.aspx
Tokyo, Japan @ http://www.kankyo.metro.tokyo.jp/kouhou/english/monitoring_today.htm
Hong Kong @ http://www.epd-asg.gov.hk/eindex.php

analysis. In the following sections, the designs and architectures implemented at each step are described in brief.

Figure 2: Modeling architecture for the air quality forecasting system



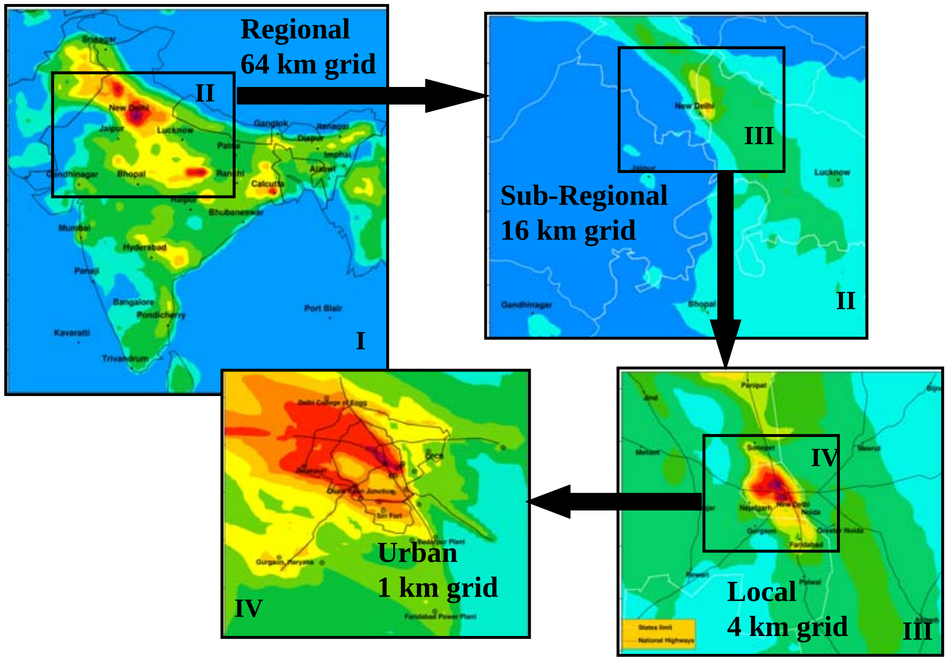
Model Nests Configuration – Regional to Urban

Though the target area for modeling is the National Capital Region (NCR) of Delhi, the meteorological and chemical transport modeling could not be conducted for this domain alone, primarily due to the complications in mathematical solutions while resolving the differential equations to process meteorological synoptics and chemical transport. Also,

- While the sources inside NCR are the primary sources of local air pollution, the sources outside Delhi also contribute significantly, via long range trans-boundary mechanisms. This is more evident from season to season. For example, dust storms from the western arid lands in early summer months; fire haze from the north and northwest during the harvest season. In order to accommodate regional phenomenon like this, the modeling system needs to be designed in a nested mode.
- Similarly, the emissions from Delhi contribute not only to the local pollution, but also to the regional pollution, via horizontal and vertical advection. This can be accommodated only in a nested mode with two way interactions as the calculations progress from one domain to the next.

In order to account for all the sources, outside and inside the target domain, it is necessary to design four modeling nests ranging from South Asia at the regional level to NCR at the urban level. The modeling domains have a single grid resolution of 64 km, 16 km, 4 km, and 1 km respectively, to accommodate the mathematical challenges in scaling down the modeling efforts to a higher resolution over Delhi.

Figure 3: Configuration of the four modeling domains



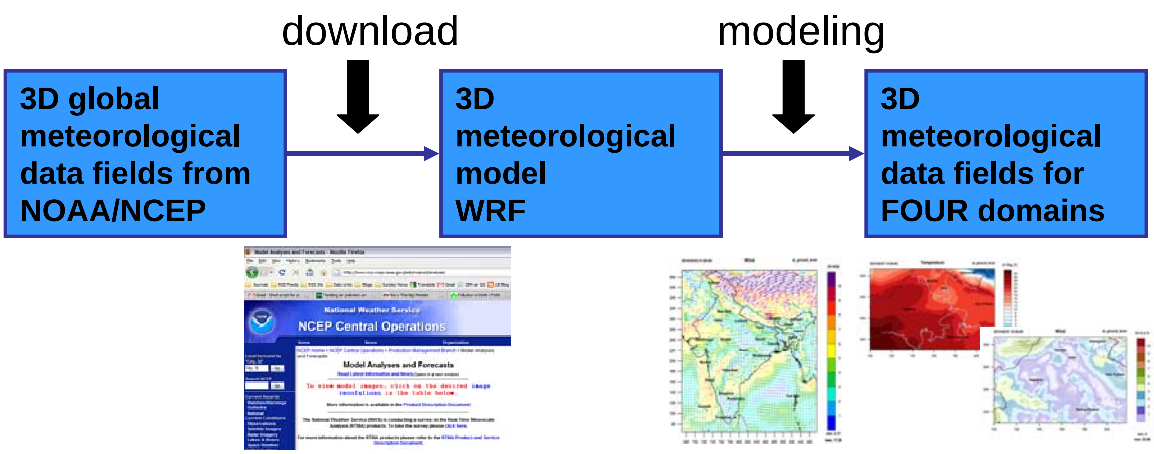
The four modeling domains (**Figure 3**) are defined as follows

- *Regional Domain*: This covers all of Indian Subcontinent of Asia at 64 km grid resolution, extending from the Afghanistan in the west to Myanmar in the east. The domain is selected to cover the regional synoptics, including the dust storms in the west. In this domain, each of the cities is modeled as one box.
- *Sub-Regional Domain*: This covers Northern India, with Delhi in the northeastern side at 16 km resolution. This domain includes the state of Rajasthan in the west, to accommodate for the occasional dust storms, which find their way into Delhi pollution. At this level, the highways tend to be visible and the cities as hotspots.
- *Local Domain*: This again covers Northern India at 4 km grid resolution, with Delhi and at its satellite cities at center. At this scale, the local affects of Delhi's own emissions begin to be visible and affect the local photochemistry.
- *Urban Domain*: This is the target domain at 1 km grid resolution, covering approximately 52 km x 52 km, ranging from Gurgaon in the southwest to Greater Noida in the southeast, from Ghaziabad in the northeast to Rohini in the northwest.

Meteorological Forecasting

The meteorological forecast is performed using the WRF (Weather Research & Forecast) model[13], is a next-generation meso-scale numerical weather prediction system designed to serve both operational forecasting and atmospheric research needs. The model features multiple dynamical cores, a 3-dimensional data assimilation system, and a software architecture allowing for parallel computing. The model has a broad spectrum of applications across scales ranging from meters to thousands of kilometers. **Figure 4** details the model configuration adopted for the forecasting system in Delhi.

Figure 4: Model configuration for meteorological forecasting



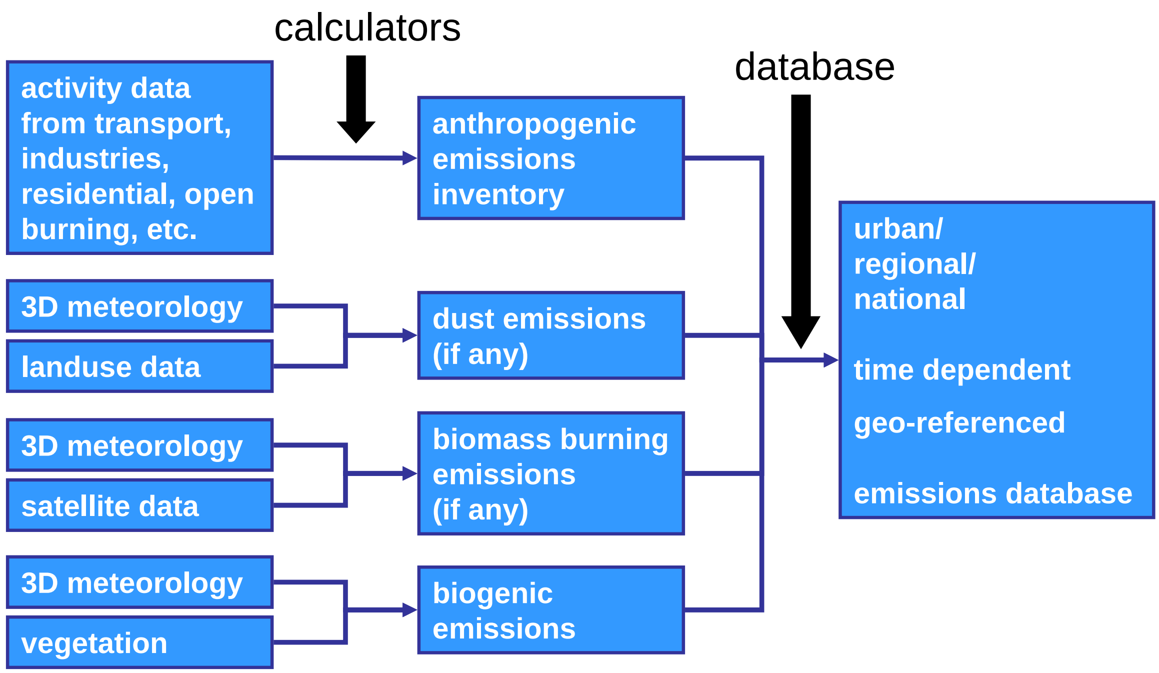
For the Delhi system, the initial and boundary conditions for the meteorological parameters are driven by the global NCEP forecasts, which are available every 6 hours at 6 hour intervals at 1° x 1° spatial resolution. The forecasts are available for 54 hours and include terrain following 3-dimensional fields of temperature, precipitation, relative humidity, wind, pressure, cloud cover, etc. The meteorological parameters modeled for a coarser grid drives the forecast for the next domain – for example, the global scale data drives leads to regional scale, which drives the forecast through the urban scale covering Delhi. At each scale, the landuse canopy and topographical affects are included to realize the regional meteorological synoptics. For the finer scales, the urban canopy and anthropogenic heat island could also be introduced, if necessary. The final outputs for each domain are available at 1 hour temporal resolution, with provision to only use the gridded fields for chemical transport modeling, but also to extract the data for either city grids (at regional scale) and points of interest at finer resolutions (urban scale).

[13] Technical details of the model, where to download, and how to utilize for similar modeling exercises is available @ http://wrf-model.org/index.php

Emissions Inventories @ National Scale

The emissions inventories at the national level and urban scale are crucial for the air quality forecasting system. The emissions inventory includes information from anthropogenic sources such as transport, industries, power plants, residential fuel usage, and similar others, and natural sources such as volcanoes, dust storms, and forest fires. The flow of information in the model is presented in **Figure 5**.

Figure 5: Model configuration for emissions processing



At the national scale, the anthropogenic emissions are substituted with the REAS database, which represents gridded inventory for sectors such as industries, domestic, agriculture, and transport, at 1° x 1° resolution, covering all of Asia[14]. This inventory is developed by Frontier Research Center for Global Change (FRCGC) for key species (PM, SO_2, NO_x, BC, CO, and VOCs) with the goal of utilizing in prediction and prognostic models that incorporates the chemical mechanisms and physical transformation of species for studying regional and global air quality.

The national inventory is further improved for 2010 with latest inventories developed for the transport, power, and residential sectors. For example, for the transport sector, **Figure 6** presents a summary of the national emissions segregated by vehicle mode. The inventory utilized is further segregated by fuel, which is not presented in this paper. In case of SO_2 emissions, the sectors with high diesel consumption, trucks, buses, and railways dominate, proportionally for the other modes. A detailed note of the methodology employed for developing the inventory will be published in the coming months.

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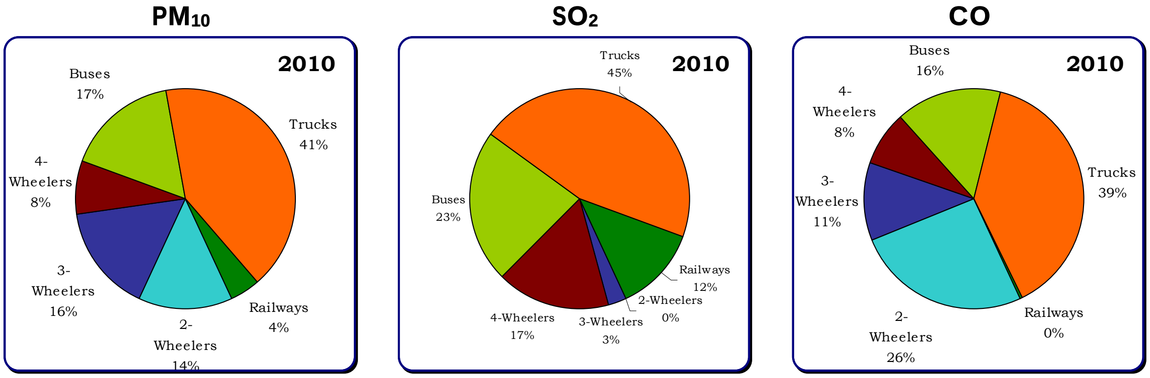
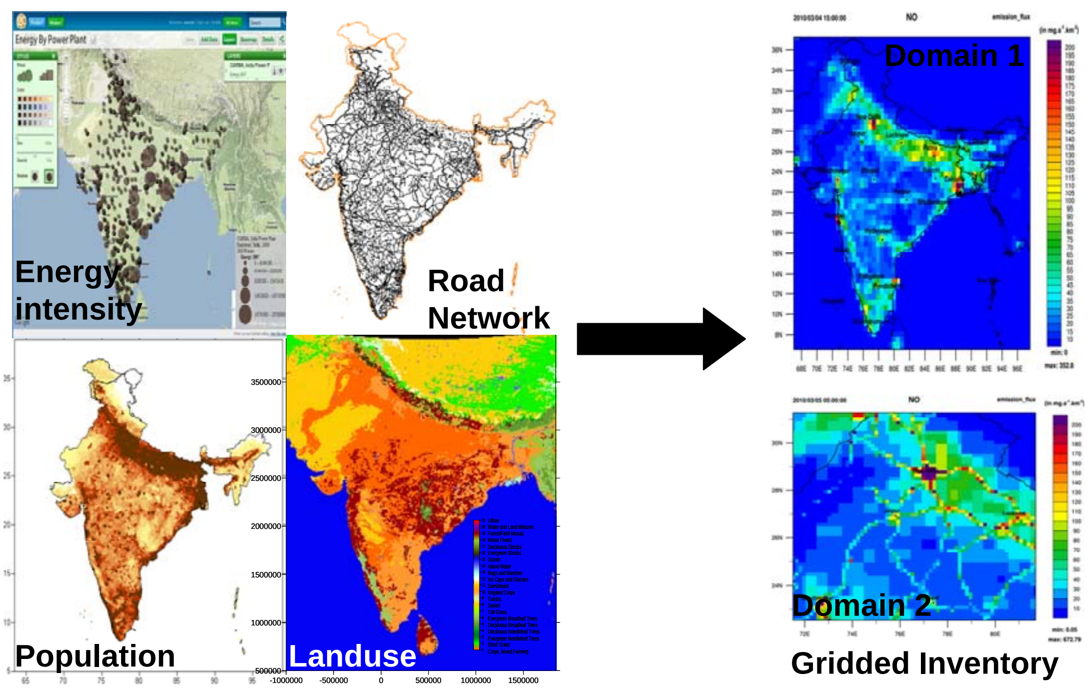
[14] The Regional Emissions Inventory for Asia (REAS) is an open source inventory for Asia available @ http://www.jamstec.go.jp/frsgc/research/d4/emission.htm

Figure 6: Summary of national transport emissions inventory



The modeling system is setup in a geo-referenced framework, which allows for detailing the source locations for each sector and visualizing the vulnerable areas. For example, **Figure 7** presents the power plant clusters (large and medium), road networks (including highways), the rural vs. urban segregations (based on gridded population) and vegetation types from the land-use. In case of the transport emissions, the distribution schemes are developed separately for each mode designated to highways (especially for trucks and ling haul buses), urban centers (for in city travel), rural roads, intercity transport (for buses). The power and industrial emissions are assigned to the source locations. The GIS databases, besides providing better spatial allocations, also allow for extraction of the results for confirmed locations.

Figure 7: Distribution mechanisms utilized for national scale emissions



At the regional scale, inventory also includes natural emissions from volcanoes, forest fires, and dust storms. These emissions are estimated using satellite observations, in case of forest fires using hot spot locations and area burnt (if any) from the MODIS satellite and some are estimated online using meteorological conditions, such as dust storms, calculated using threshold wind speeds to simulate the uplift of dust from arid regions of South Asia. The module "Wildfire" based on model WRF-CHEM[15] is integrated into the modeling system to account for the forest fire emissions in the domain 1 and domain 2 regions. This module is dedicated to forecast the emissions of pollutants due to forest fire such as CO, NO_x, VOC, SO_2, and Ammonia in gas phase and Black Carbon, Organic Carbon in particulate phase. The steps involved in processing the available information is as follows

- Download hotspot information[16] such as spot location and its brightness from MODIS satellite (**Figure 8**)
- Calculate the pollutant emissions by combining hotspot information with meteorology and geographical landuse information
- These emissions are considered as biogenic surface emissions and input into CHIMERE.

Figure 8: Examples of satellite imagery on dust storms and forest fires[17]

Dust over Northern India June 2nd, 2010 | **Fire hotspots over Northern India - November 8th, 2009** | **Hotspot counts from 23/10/2010 to 25/10/2010**

The inventory also includes the biogenic sources (such as isoprene), which play a critical role in the photochemistry affecting the production and destruction of ozone over the green covers. An important input for this source is the landuse database, which is available at 30 sec (~1 km) resolution from the United States Geological Survey. The model adapted in this system to estimate and distribute the biogenic emissions is called MEGAN[18]. An example of gridded emissions inventory including the anthropogenic and natural sources is presented in **Figure 7 (right panel)**.

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[15] WRF-Chem @ www.mmm.ucar.edu/wrf

[16] Hot spot information on the forest fires from MODIS satellite @ http://firefly.geog.umd.edu/firemap

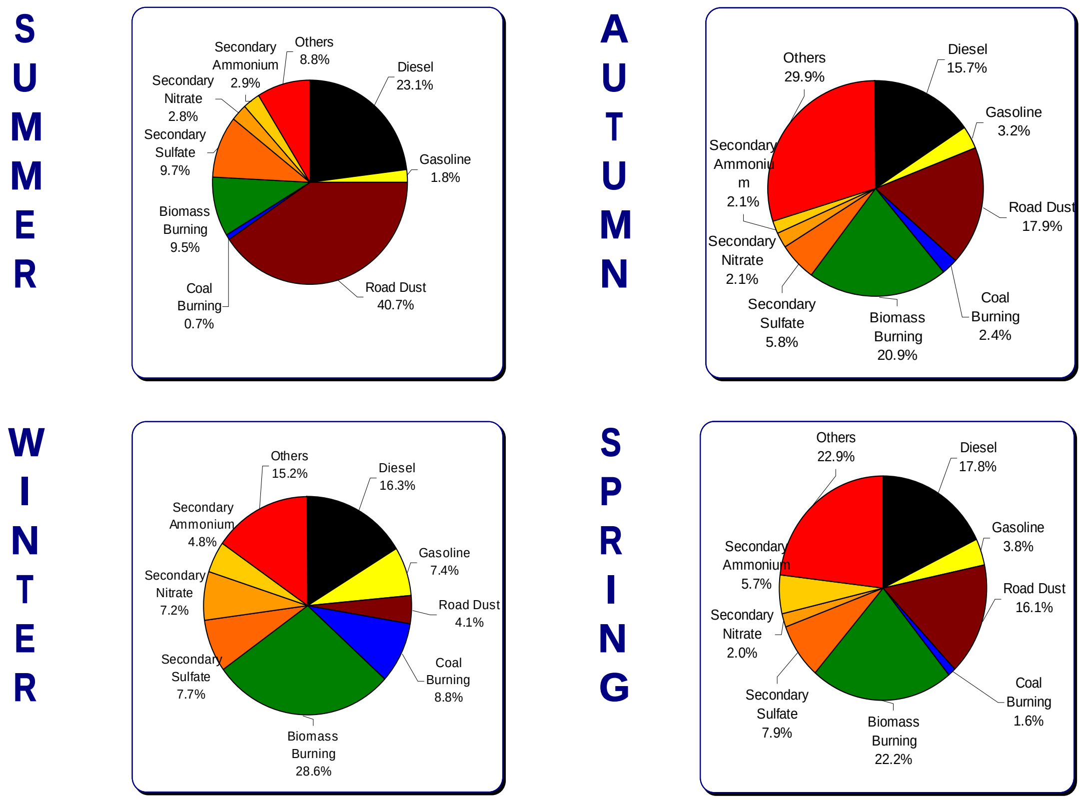
[17] The images from from MODIS (Moderate Resolution Imaging Spectroradiometer) satellite. Details of products from MODIS are available @ http://modis.gsfc.nasa.gov/
Dust observed on June 2nd, 2010 @ http://earthobservatory.nasa.gov/NaturalHazards/view.php?id=44172
Hotspots observed on November 8th, 2009 @ http://earthobservatory.nasa.gov/NaturalHazards/view.php?id=41241

[18] Model of Emissions of Gases and Aerosols from Nature (MEGAN) is utilized for biogenic emissions. Details on the model and references @ http://acd.ucar.edu/~guenther/MEGAN/MEGAN.htm

Emissions Inventories @ Urban Scale

Similar to regional scale inventories, for the urban scale covering the NCR of Delhi, an emissions inventory was developed including all key species – PM, SO_2, NO_x, BC, CO, and VOCs. No single sector is solely responsible for Delhi's air pollution. Rather, it is a combination of sources including industries, power plants, domestic combustion of coal and biomass, and transport (direct vehicle exhaust and indirect road dust) that contribute to air pollution, though the contribution proportion may vary.

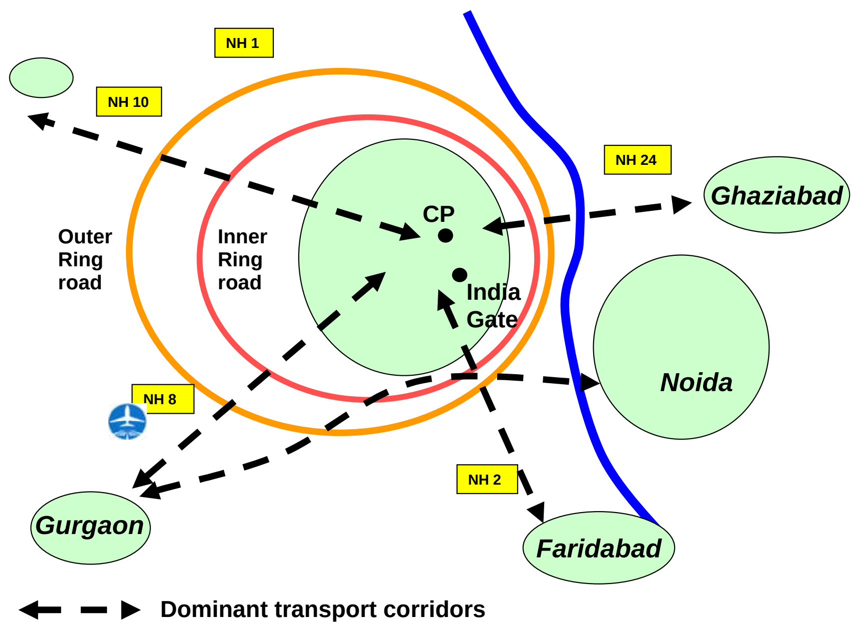
Figure 9: $PM_{2.5}$ Source apportionment results for Delhi



Seasonal changes in demand for fuel and natural pollution result in differing sources during the summer and the winter months. These need to be taken into account to maximize the effectiveness of anti-pollution initiatives. **Figure 9** presents the results of particulate matter source apportionment of the urban air pollution in Delhi, conducted by the Georgia Tech University (USA) in 2005.

In summer, in addition to the road dust already present on the Delhi roads, dust storms from the desert, to the south-west (discussed in the earlier sections), contribute to increased fugitive dust, enhanced by growing vehicular movement. 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 summer, biomass accounts for only 9 percent of particulate pollution.

Figure 10: Graphical representation o the National Capital Region and the travel demand from the satellite cities



Another external factor of pollution is agricultural clearing (discussed in the earlier section). After the harvesting of crops, clearing agricultural land is a common practice in surrounding (largely agricultural) states. The smoke reaches Delhi and contributes to the smog formation and ozone pollution.

Apart from biomass burning and ambient dust, transportation and industries are major contributors. With a growing city, the corresponding transportation needs are fueling a rise in private vehicles (2 and 4 wheelers), taxis and autorickshaws. As a result, operating traffic speeds have reduced for all vehicles, thus increasing idling time and pollution. Industry, the other major source – accounts for about a fifth of air pollution and includes five power plants, at Indraprastha, Faridabad, Badarpur, Pragati, and Rajghat (using a mix of coal and natural gas for electricity generation), ~3,000 industries ranging from pharmaceutical to metal processing, that use coal, fuel oil, and biomass.

The growing industrial conglomerations and information technology (IT) parks, under the Special Economic Zone (SEZ) schemes have also led the way in increasing the travel demand. This led to a significant change in the geographical settings, the travel behavior and the mode of transport (transformed to motorized transport) and not only increased the vehicle kilometers traveled per day, but also exerting pressure on the limited infrastructure, results in congestion, idling, and pollution (see **Figure 10**). On a daily basis, in and out travel between Delhi and the satellite cities account for nearly 30-40 percent of the passenger trips. These satellite cities are also prone to regular power cuts, leading to increasing use of generator sets for in-situ 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, resulting in deteriorating air quality, increased trip costs, extended commuter times, meaning longer exposure to increasing pollution and health impacts.

Table 1: A summary of the emissions inventory for 2010 for NCR of Delhi, India

	PM10	PM2.5	SO2	NOx	CO	NMVOC
Source	**59,898**	**28,877**	**41,941**	**157,128**	**574,616**	**238,042**
Transport	4,911	4,011	1,166	110,678	419,600	179,519
Power Plants	7,338	5,871	18,656	20,008	36,143	1,690
Residential - Cooking	1,097	880	358	225	19,206	2,529
Commerical	1,706	1,279	6,295	1,624	23,812	8,844
Industries	4,578	2,747	15,234	23,340	53,431	43,440
Waste Burning	4,903	3,478	232	1,253	22,424	2,020
Road Dust	35,365	10,610	-	-	-	-

A comprehensive emissions inventory 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, was developed for the year 2010 for application and to analyze in the air quality forecasting system.

Figure 11: Percentage contributions to the emissions inventory for 2010

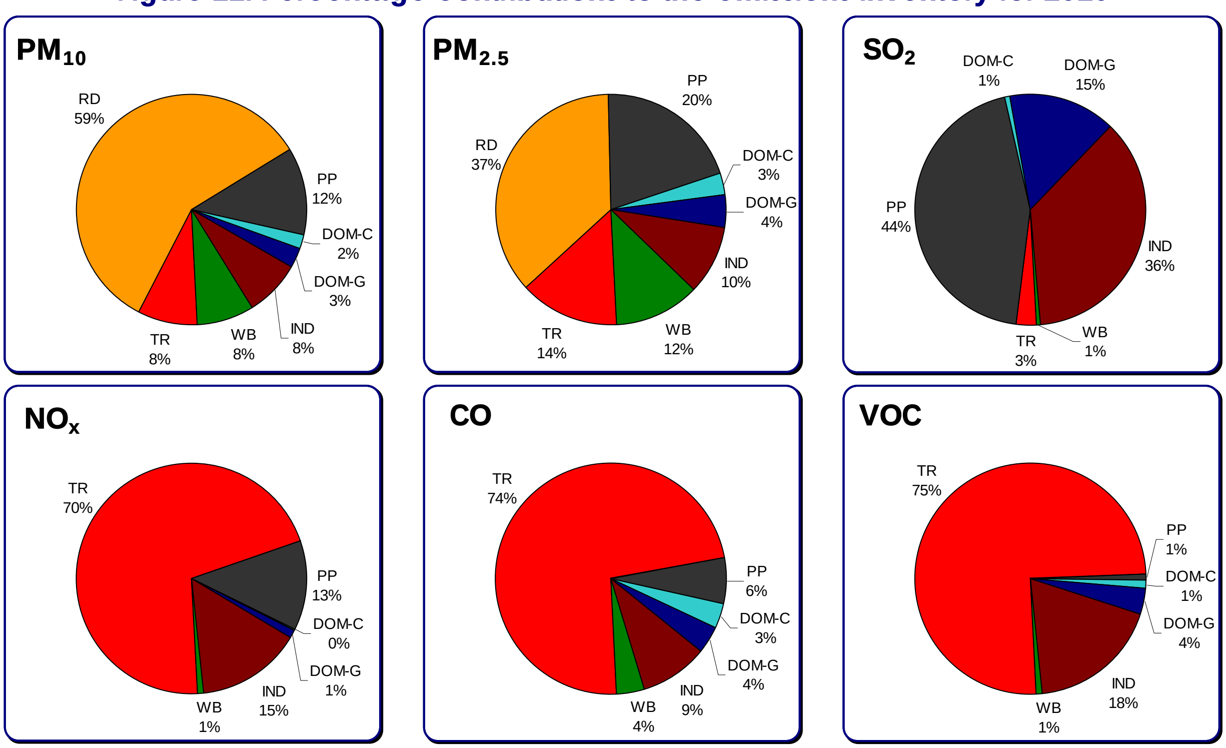
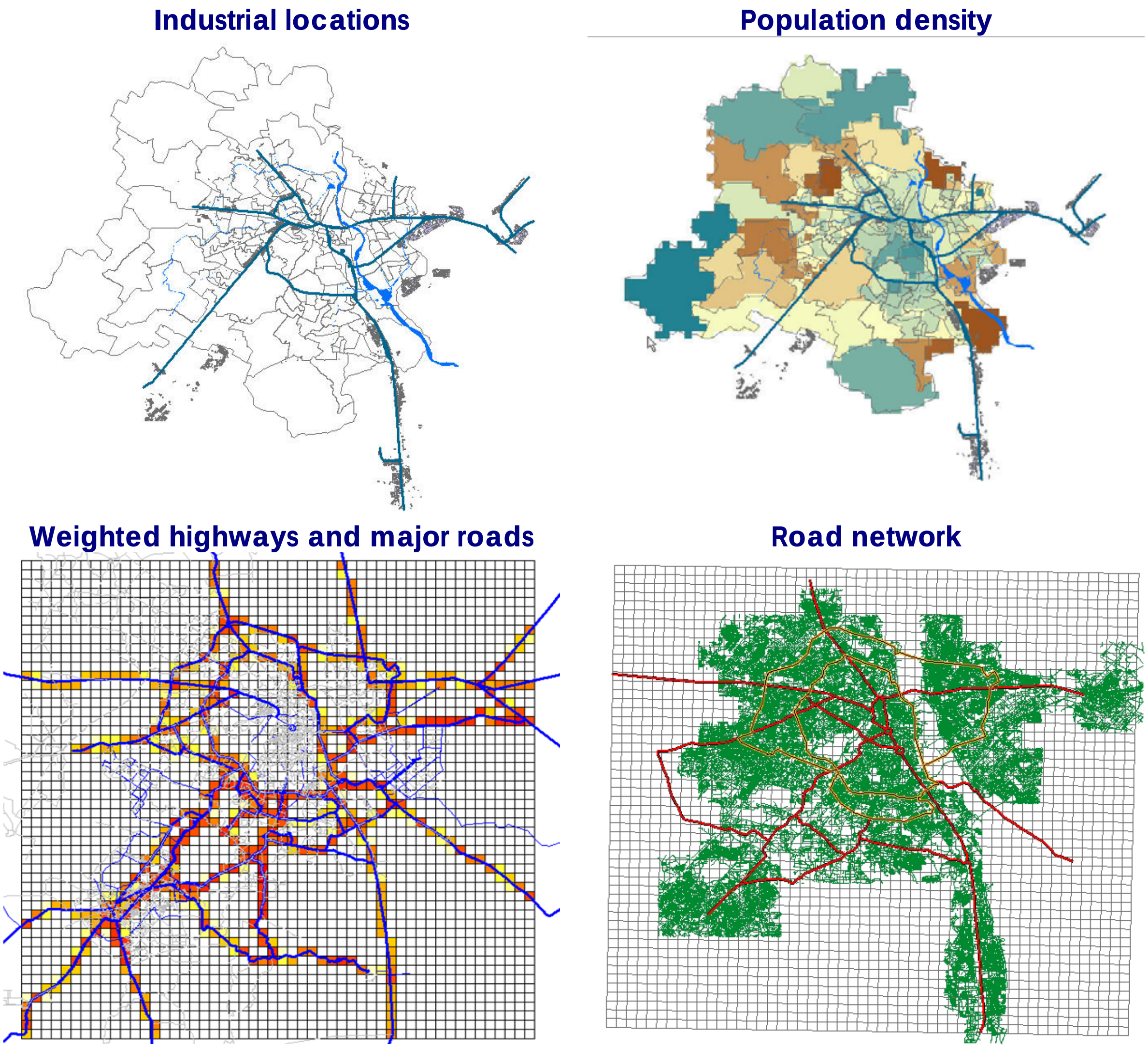


Table 1 presents a summary of the emissions inventory for year 2010, as utilized in the forecast modeling system for launch before the Commonwealth Games and the percentage breakup by sector is presented in **Figure 11**. Unlike the national inventory, where gross level estimates are made at the city level, the urban scale emissions inventory requires more detailed information at a much finer resolution. The final emissions inventory is now available @ 1km x 1km grid resolution covering an area 52km x 52km.

Figure 12: Distribution mechanisms utilized for urban scale emissions

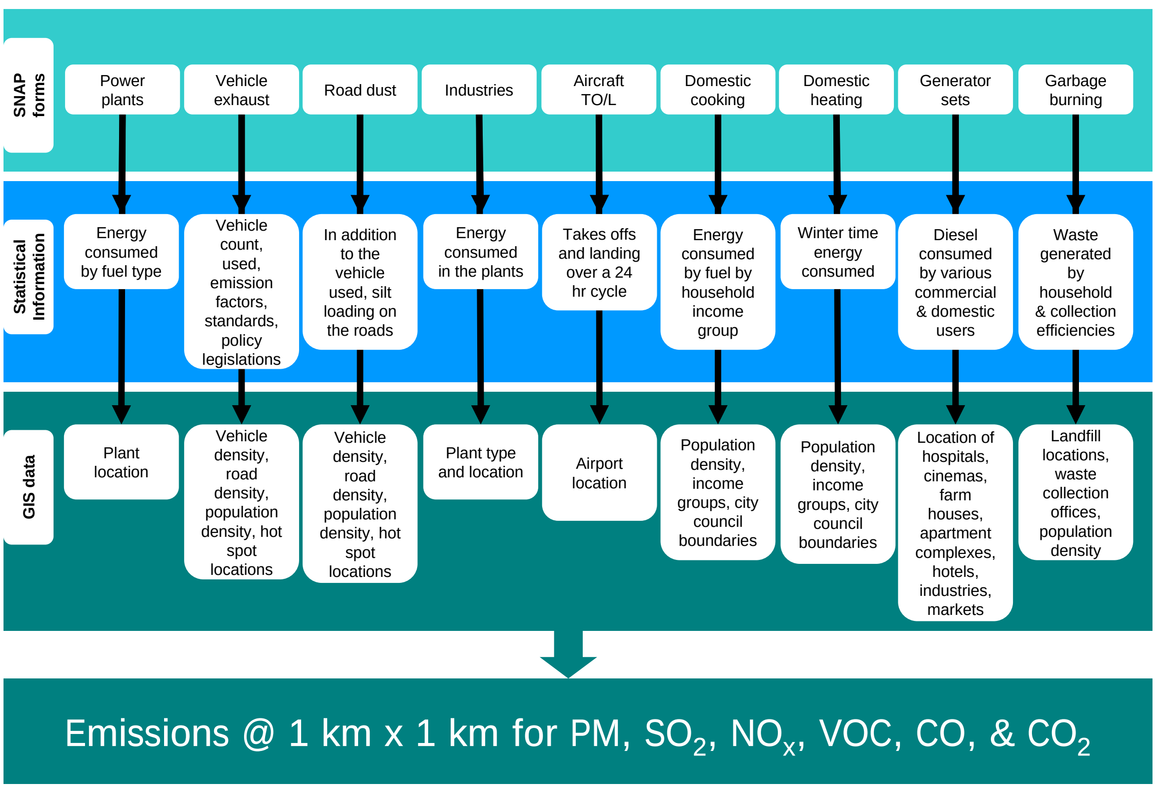


By far, the transport sector dominates the emissions inventory from direct and indirect emissions. For example, the PM emissions are sourced most to the resuspension of road dust due to vehicular movement followed by vehicular exhaust, mostly from the diesel used in the passenger cars and the trucks. Following the transport sector, the industries, power plants, and generator sets (in the commercial and domestic sector, to compensate for frequent shortages) are the dominant sources of emissions. The road dust is classified as the resuspension emissions due to the vehicular movement on the roads, which is dependent on the silt loading by road types, average vehicle speeds and average tonnage.

The urban inventory is further segregated spatially (**Figure 12**) 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.

Similar to the regional scale emissions inventory, the urban emissions inventory is also 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). Various levels of statistical and geographical information databases[19] collected and utilized in the analysis and the line of calculations employed for spatially allocating the urban emissions to the 1 km x 1 km grid cells is presented in **Figure 12**.

Figure 13: Flow of information utilized for spatial allocation of urban scale emissions



At the end of the calculations chain presented in **Figure 13**, the model-ready emission inventory is developed on a geo-referenced platform for immediate use in the chemical transport modeling. The segregations by sector, by fuel, and by pollutant is maintained throughout the calculations, to allow the user to conduct possible scenario analysis with or

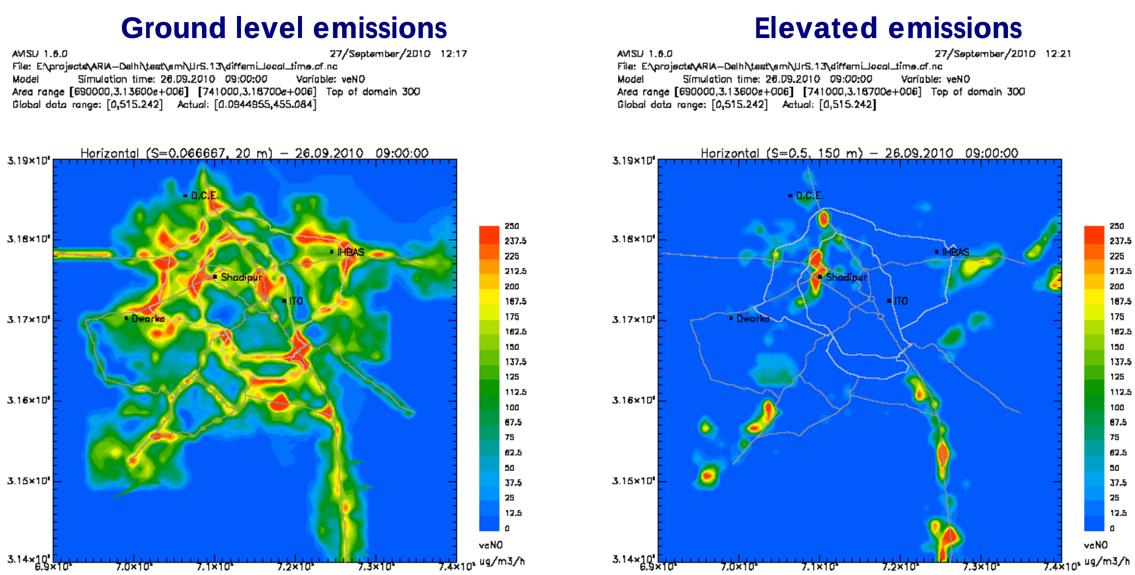
[19] All the databases are proprietary information purchased from the Eicher group in New Delhi, India

without a particulate segment, or even allow the user to make changes to the inventory without having to disturb the entire chain of calculations.

The model-ready emissions inventory also includes diurnal cycles for the transport sector 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. For example, in Delhi, and other cities in India, heavy duty trucks are not allowed to pass through the city during the day time. The trucks are allowed to enter the zone after 9 PM and stop at 6 AM. Similarly, the light duty trucks, which are used for commercial transport within the city, also have restrictions of not able to operate during the morning rush hours. The forecast systems allows the user to introduce as many diurnal cycles as possible and as segregated as possible for each of the vehicle and industrial type. These diurnal cycles are constantly updated and varied to accommodate weekday/weekend and seasonal changes.

The emissions inventory is further developed in three dimensions to account for the elevated sources such as power plants and the industries. **Figure 14** presents summary graphs for the emissions inventory in three dimensions.

Figure 14: Three dimensional representation of the emissions inventory



Finally, all the data from aggregate emissions inventory, by fuel, sector, and mode, to the diurnal, weekly, and seasonal profiles, the information is stored as a package called ***the Emission Manager software*** which processes and prepares model-ready inputs for the chemical transport models.

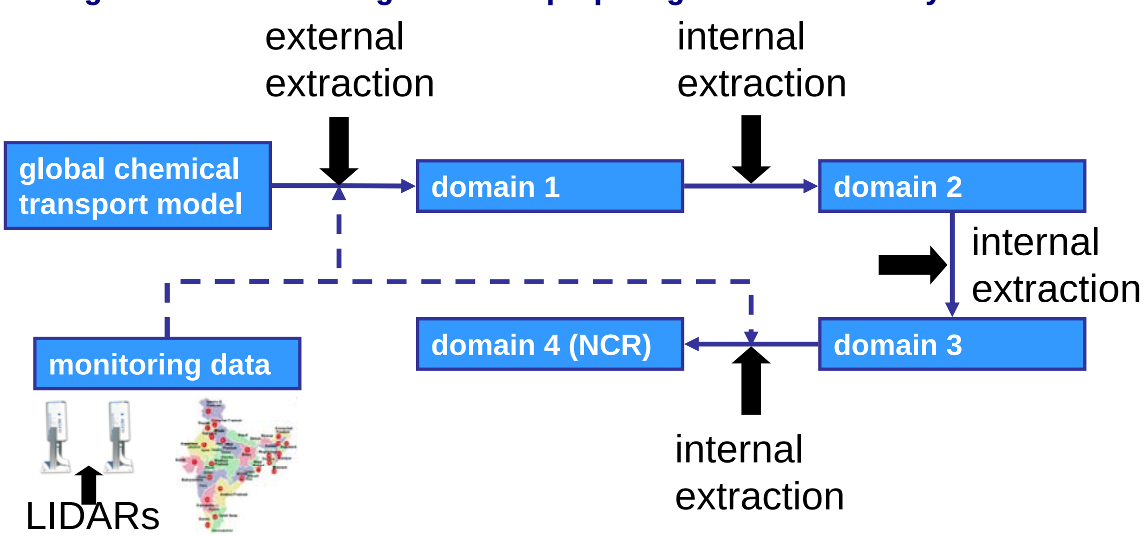
Initial and Boundary Conditions for All Domains

The initial and boundary conditions are very important for the chemical transport modeling for the following reasons.

- The initial conditions establish a baseline for the model, to initialize the species and radical concentrations and to drive the model for further simulations.
- Similar to the reason why the modeling system is established in a nested format - the need to include the external sources, the boundary conditions establish the necessary information.

Both the initial and boundary conditions are very essential, in order for the modeling system to represent the long-range of pollution from regional to urban scale. For the urban scale simulations, the Boundary conditions are usually established from a model run with low resolution, which in this modeling system is the domain-3 presented in **Figure 3**. However, the initial conditions are established from the model simulations conducted for the same domain the previous day for the start date and time, along with the data from the monitoring networks available to the end-user.

Figure 15: Model configuration for preparing initial & boundary conditions

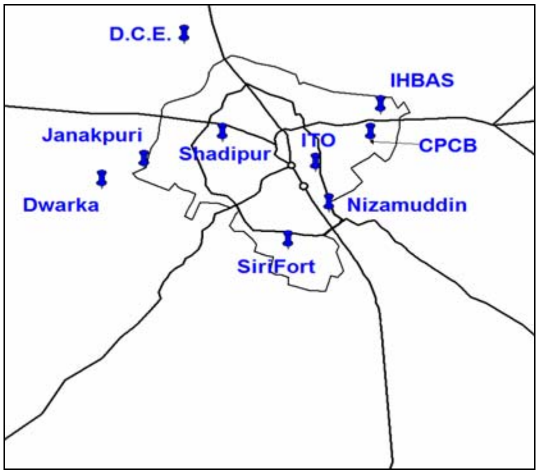


The configuration of how the initial and boundary conditions are utilized in the model is presented in **Figure 15**. For domain 1, the first set of conditions is derived from the MOZART global model (external extraction). This is also supplemented with monitoring data from the 350 stations operated by CPCB across India in 172 cities. The data from these stations is limited in temporal and spatial resolution, but helps in calibrating the model initialization. The extraction of the initial conditions from the global model is a one time extraction, which later is substituted by the results from previous day simulations.

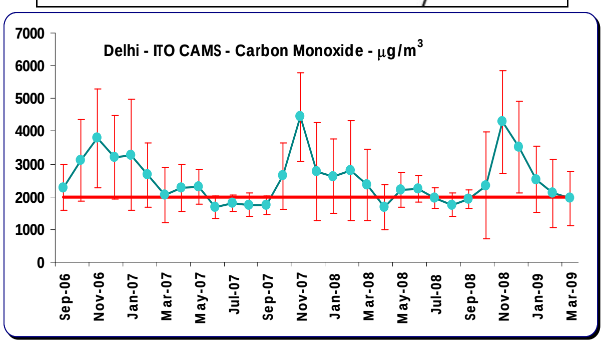
Since the later domains are subset of each other, the results from domain 1 drives domain 2, results from domain 2 drives domain 3, and domain 3 drives domain 4 simulations. These are considered internal extractions which are automated into the modeling chain on a day to day basis.

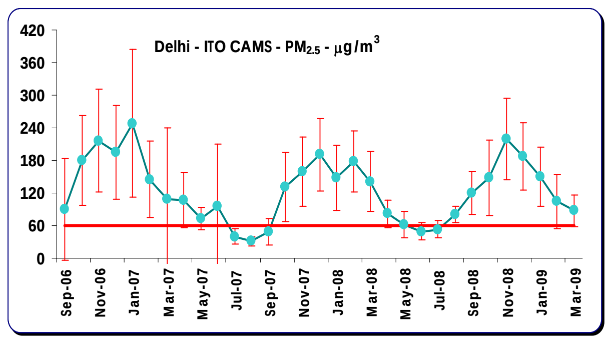
For domain 4, the conditions are further supplemented with data from the local monitoring network. The **Figure 16** presents the monitoring network in Delhi and a summary of the data for two pollutants from the ITO station.

Figure 16: The ambient air quality monitoring network in Delhi



(illustration of Continuous Air Monitoring System)

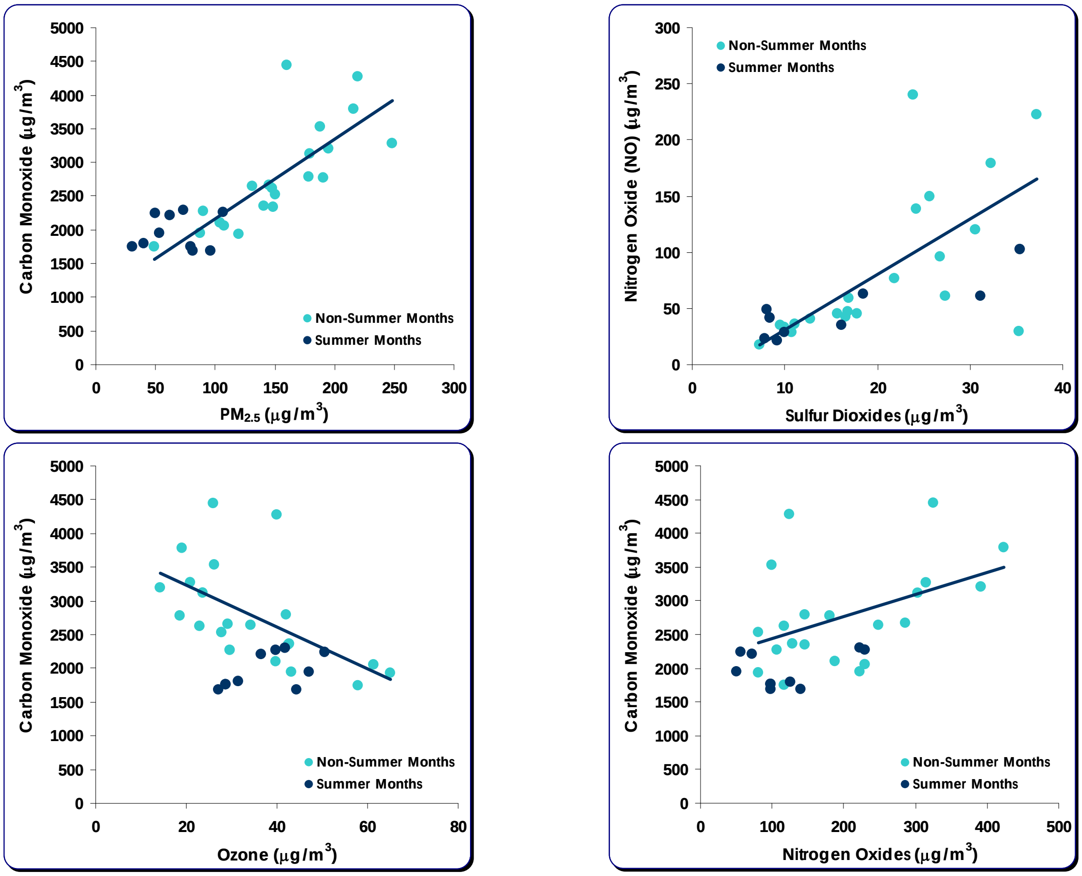




The pollution measured around the ITO station is primary in nature; more linked to the direct emissions and proximity to the sources. This is evident in the correlations (**Figure 17**) between the tracer pollutants like CO, NO, SO_2, and $PM_{2.5}$. Note that the Figure indicates measured concentrations and not the emissions, and they are only indicative of the local 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.

Figure 17: Correlations between criteria pollutants of measured daily averages (2006-09) at the ITO station in Delhi, India



The data from each of the monitoring stations is further utilized for developing the initial conditions and also to support the chemical mechanisms used in the model.

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 17 (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 17**, **bottom left**) and the oxidizing capacity of NO_x, details of which are described in the following section.

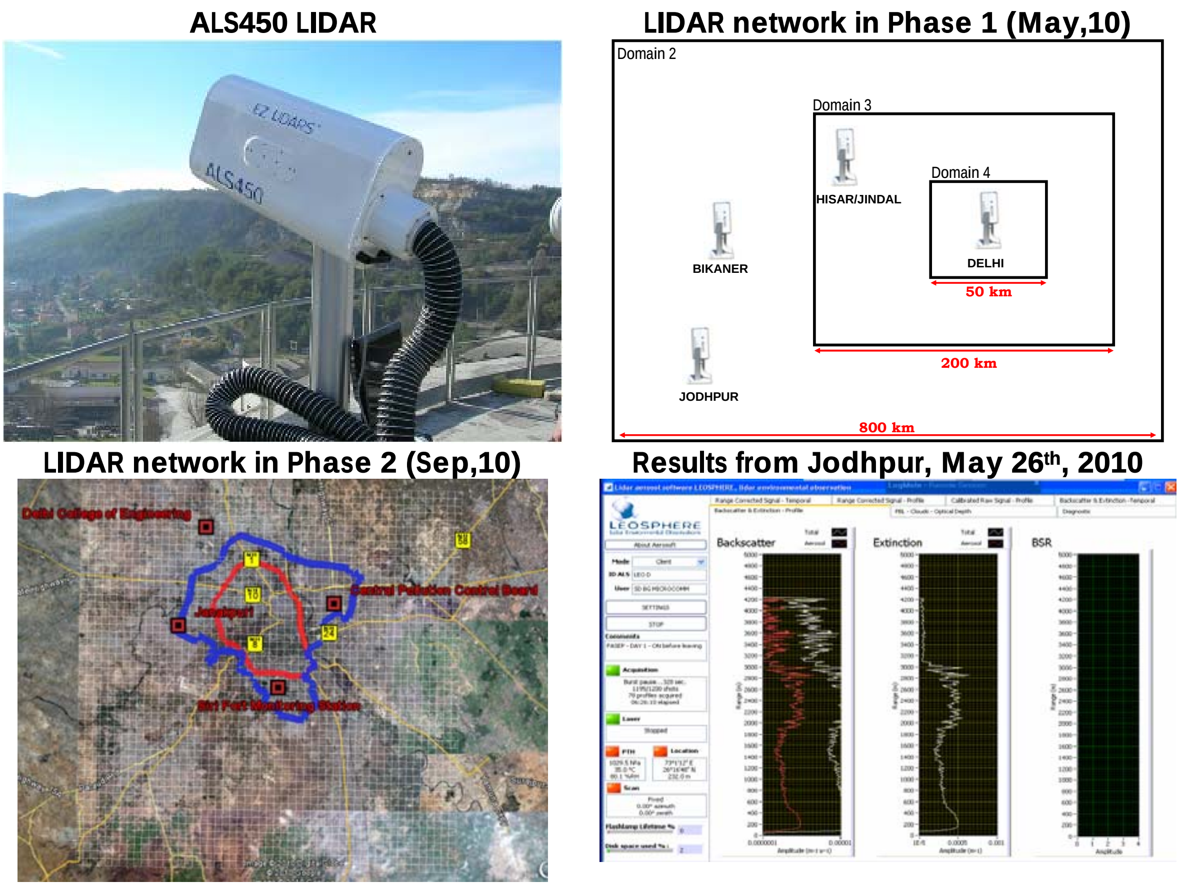
The monitoring data processing is further enhanced with a LIDAR network[20], deployed in two phases for this study. LIDAR (Light Detection And Ranging) works on optical remote sensing technology to measure aerosol concentrations and wind (speed and direction). Since the technology is based on optical properties, the accuracy level for this methodology is very

[20] The LIDAR network is supplied and operated by the Leosphere SA, Paris, France

high, though limited to aerosol concentrations and wind. The data from the LIDAR network is designed to support the development of initial and boundary conditions, not only at the ground level, but also the vertical profiles.

While the traditional monitoring stations provide point measurements for pollutants and meteorological features, a single LIDAR (**Figure 18**) can provide horizontal profiles when used parallel to the ground for at least a radius of 2 km, depending on the obstacles and vertical profiles for a distance of 7-10 km when pointed upwards.

Figure 18: LIDAR network to support the monitoring data @ Regional and Urban Scale



The LIDAR data is rich, which can be utilized for establishing hot spot locations across the city and also studying the long range transport of pollution, such as dust storms, which is normally observed at altitudes above 1 km, which is not possible with traditional monitoring stations. In **Figure 18 (right top)**, the LIDAR network presents a configuration to capture the summer time dust storms originating from Rajasthan's Thar desert. The LIDARs at Jodhpur and Bikaner (Rajasthan) were used to capture the dust signals and alerts the systems place in the Domain 4 (Delhi) at the National Physical Laboratories (NPL). The **Figure 18 (right bottom)** panel presents example results of light scattering from Jodhpur station during the Phase 1 operation (May-June, 2010), pointing out a dust event at 2-3km altitude on May 26th, 2010, which was later captured by the Delhi station. Furthermore, the remote sensing technology is now advanced enough with mathematical algorithms, to distinguish between biomass burning, dust, and anthropogenic pollution, which will be used to analyze the LIDAR data.

In Phase 2, September-October, 2010, five LIDARs (4 stationary and one mobile) were deployed across Delhi, all in Domain 4 (**Figure 18 - left bottom**), to capture urban signals and help collect as many profiles as possible to support the air quality forecasting system, along with the data from monitoring stations operated by CPCB and DPCC.

Figure 19: Pictures of the LIDAR installed in a van, powered by a generator

The interest of running lidars in this second phase turned into two complementary directions, related to sources and atmospheric dynamics, respectively:

- To provide vertical structures of the atmosphere in TPM, as for Phase 1, in order to be compared to the vertical distribution of particles modeled. A greater attention was paid to the lower layers, as local sources effects supposedly varied from one lidar site to the other.
- To monitor in real time, and hence better understand, the diurnal variability of the mixing layer - or planetary boundary layer (PBL) - height. The reliability for air quality models of this key parameter, since it affects the dilution/concentration of the surface layer pollutants, is especially limited at the urban scale. Lidars therefore offered the model to run scenarios using constrained PBL data, in order to lower the uncertainty associated to their outputs and possibly identify and quantify the limitations imposed by other factors (emission source inventories for instance).

Chemical Transport Dispersion Modeling

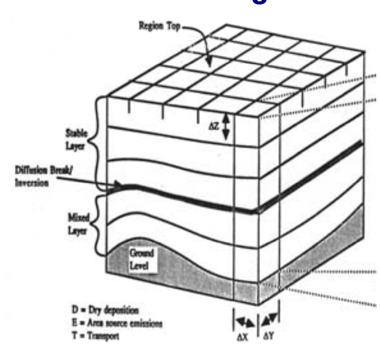
Common Misconception - Modeling and forecasting is entirely based on monitoring data: This is FALSE. The monitoring data, in its true form, is not utilized directly to model or forecast the air quality. The modeling is a bottom-up exercise following a series of steps, starting with emission inventory development not only for the area of interest, but also covering external areas to support boundary conditions, include transboundary impacts. The process involves dispersion of the emissions through a chemical transport model using assimilated meteorological conditions (in this case from the WRF modeling system), and exposure assessment and scenario analysis. During this process, the monitoring data, in many forms and from multiple sources (in this case from ground based monitoring and LIDAR networks) is used to calibrate and validate the methodologies applied.

The forecasting exercises commonly utilize the eulerian dispersion models with full chemistry, in conjunction with an established emissions inventory for key species, meteorological fields for the domains, and initial and boundary conditions. For the system in Delhi, two such models are employed.

- CHIMERE – for Domain 1 (regional) and Domain 2 (sub-regional) simulations
- FARM – for Domain 3 (local) and Domain 4 (urban) simulations

Both the models are well established and utilized for multiple applications across the world.

Figure 20: An illustration of eulerian dispersion model



$$\frac{\partial c_i}{\partial t} = -u\frac{\partial c_i}{\partial x} - v\frac{\partial c_i}{\partial y} - w\frac{\partial c_i}{\partial z} \quad \text{(advection)}$$

$$+ K_{xx}\frac{\partial^2 c_i}{\partial x^2} + K_{yy}\frac{\partial^2 c_i}{\partial y^2} + \frac{\partial}{\partial z}\left(K_{zz}\frac{\partial c_i}{\partial z}\right) \quad \text{(turbulent diffusion)}$$

$$+ S_i + C_i + R_i$$

sources; gas-phase reactions; dry & wet removal

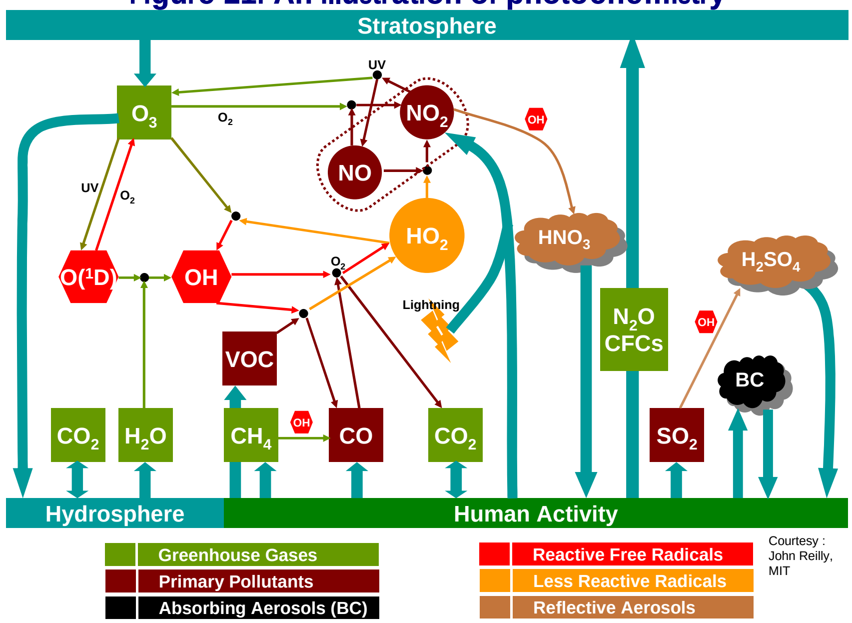
In short, an Eulerian model looks at the advection of pollutants and radical species across each grid in 3-dimensions, including the chemical transformation during the species that stay in the grid box.

The chemical mechanism in the model is crucial, which eventually drives the pollutant concentrations from hour to hour, producing and destructing chemical species along the way[21]. The urban air pollutants arise from a wide variety of sources, linked to their

[21] A number of well studied chemical mechanisms were established at varying degrees of complexities by the "chemical transport modeling community". These mechanisms cover a wide range of species – direct and indirect, radicals, photolysis schemes, and some even include gas-aerosol interactions in multiple size bins to support the extensive chemical analysis. Commonly known chemical schemes include
1. Statewide Air Pollution Research Center (SAPRC) chemical mechanism
@ http://www.engr.ucr.edu/~carter/pubs/#reports

respective combustion processes. The largest sources include the motor vehicles, variety of manufacturing processes (industries) such as brick kilns, cement, metal processing, tanning, etc., residential fuel usage, biomass burning and road dust (especially in the developing country cities) and each with specific chemical composition for the key pollutants such as NO_x, CO, VOCs and PM. Given the mix of NO_x and VOC emissions, combined with strong sunlight during the day, this leads to a buildup of Ozone through photolysis and aide of numerous radicals. A summary of the photochemical processes is presented in **Figure 21**. The chemical mechanism employed in the CHIMERE and FARM models includes ~300 chemical reactions involving ~100 species.

Figure 21: An illustration of photochemistry



Although the urban photochemistry is well documented, some of the aspects of chemistry that relate to ozone sensitivity and indicator species is worth summarizing.

In an urban environment, during the rush hours, following the increase in the emissions of NO_x and CO, Ozone concentrations built up rapidly after sunrise, immediately followed by reduction in NO_x and CO concentration owing to oxidation by Ozone and other hydroxyl radicals. In the evening, a reverse phenomenon is observed where the photo-chemical activity reduces at sunset, increasing the CO and NO_x concentrations owing to less Ozone for initiation of oxidation process and an increase in the emissions from the diesel trucks.

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2. Regional Atmospheric Chemistry Mechanism (RACM)
@ http://www.agu.org/pubs/crossref/1997/97JD00849.shtml
3. Carbon Bond IV Mechanism (CBM IV)
@ http://www.epa.gov/scram001/photochemicalindex.htm
@ http://www.ccl.rutgers.edu/~ssi/thesis/thesis-node57.html
Also see "Fundamentals of Atmospheric Modeling" by Dr. Mark Jacobson, Stanford University
@ http://www.stanford.edu/group/efmh/FAMbook2dEd/index.html
"Atmospheric Chemistry & Physics" by Dr. Sienfeld and Dr. Pandis
@ http://www.amazon.com/Atmospheric-Chemistry-Physics-Pollution-Climate/dp/0471178160

The conversion of NO to NO_2 (via an oxidizing agent) and NO_2 to NO (via ***photodissocation***) results in the production or destruction of ozone and formation of the intermediates $O(^3P)$ (ground state oxygen atoms) as represented in **Equation 1**. In the following equations, intermediate radicals are indicated with a closed dot next to each species.

$$\begin{aligned} &NO + OH \rightarrow NO_2 + H^\bullet \\ &NO_2 + hv \rightarrow NO + O(^3P)(\lambda \leq 400nm) \\ &O(^3P) + O_2 \rightarrow O_3 \\ &NO + O_3 \rightarrow NO_2 + O_2 \end{aligned}$$

(**Equation 1**)

However, in the presence of the hydrocarbons, the NO+O_3 reaction in **Equation 1** becomes less important in removing the ozone produced, since much of the NO is oxidized to NO_2 by hydrocarbons rather than by ozone; the hydrocarbons compete with ozone for the NO.

$$\begin{aligned} &RH + OH \rightarrow R^\bullet + H_2O \\ &R^\bullet + O_2 \rightarrow RO_2^\bullet \\ &RO_2^\bullet + NO \rightarrow RO^\bullet + NO_2 \\ &NO_2 + hv \rightarrow NO + O(^3P)(\lambda \leq 400nm) \\ &O(^3P) + O_2 \rightarrow O_3 \end{aligned}$$

(**Equation 2**)

In polluted environments, as measured in the case of Delhi, CO also contributes to ozone production via reaction with OH radicals and subsequently with NO.

$$\begin{aligned} &CO + OH \rightarrow H^\bullet + CO_2 \\ &H^\bullet + O_2 \rightarrow HO_2^\bullet \\ &HO_2^\bullet + NO \rightarrow HO^\bullet + NO_2 \\ &NO_2 + hv \rightarrow NO + O(^3P)(\lambda \leq 400nm) \\ &O(^3P) + O_2 \rightarrow O_3 \end{aligned}$$

(**Equation 3**)

Besides, anthropogenic and biomass CO, CO is also generated during the chemical conversion of hydrocarbons resulting in net production of ozone. Examples of the conversion of methane (CH_4) and ethene (C_2H_4) are illustrated in **Equation 4**.

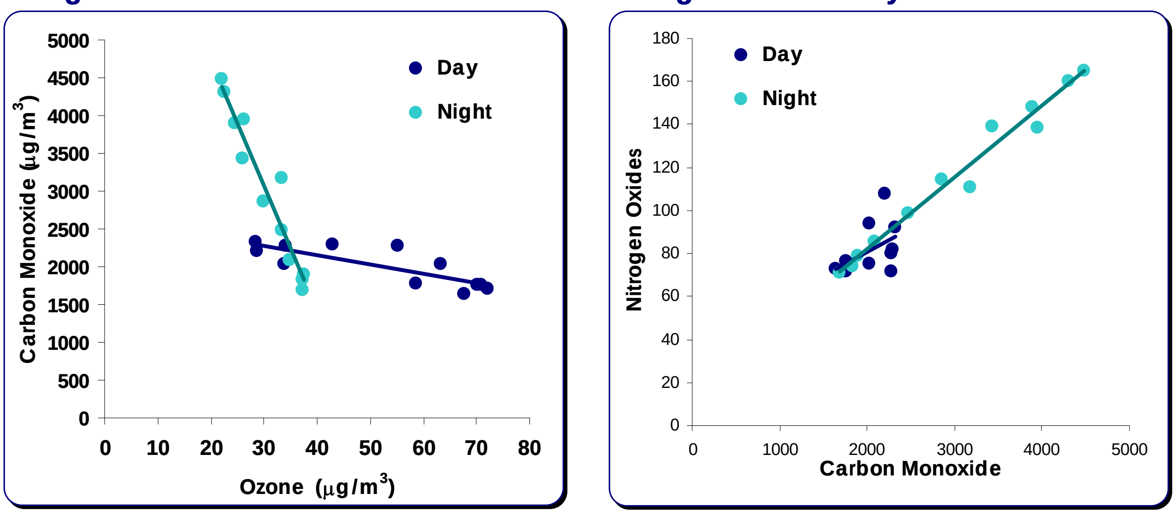
$$\begin{aligned} &CH_4 + NO + OH + 2O_2 \rightarrow HCHO + HO_2^\bullet + H_2O + NO_2 \\ &C_2H_4 + OH \rightarrow HCHO + RO_2^\bullet \\ &HCHO + hv + 2O_2 \rightarrow CO + HO_2^\bullet (45\%) \\ &HCHO + hv \rightarrow CO + H_2 (55\%) \\ &HCHO + OH^\bullet + O_2 \rightarrow CO + HO_2^\bullet + H_2O \end{aligned}$$

(**Equation 4**)

The formaldehyde (HCHO) is an important intermediate species, which is very short lived undergoing photolysis during the daytime converting to CO, NO_2 and hydrocarbon radicals, which result in net production of ozone. A major source of HCHO in a polluted boundary layer is the chemical conversion of Alkanes (e.g., Methane, Ethane), and Alkenes (e.g., Ethene). Major source of VOCs is the incomplete combustion in the vehicles because of improper maintenance and even adulteration of the fuel, among many reasons. The products of the reaction of hydrocarbons with NO also include other nasty photochemical pollutants such as PAN (peroxyacetyl nitrate), both toxic and irritating.

However, in an urban environment, in NO_x rich conditions, NO also reacts with ozone producing NO_2 and HNO_3, determining the steady state called ***photostationary state reaction***. At the ITO monitoring site, the NO_2 during the day time (**Figure 22**, **right**) reaches a steady state concentration of ~70 μg/m^3.

Figure 22: Correlation between diurnal averages over all days in 2008 in Delhi

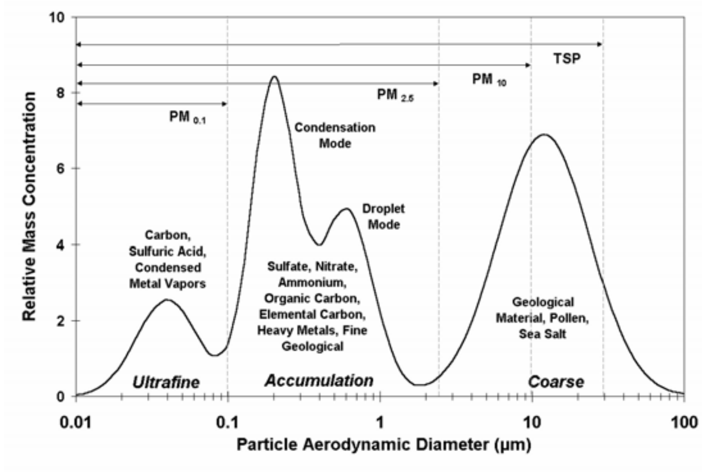


At night, with no sunlight, reaction of NO and O_3 is slower, resulting in lesser oxidization of the CO pollution and net destruction of ozone; while the opposite is observed for during the day time (**Figure 22**, **left**). On the other hand, in an area where VOC (including CO) to NO_x ratio is higher, reaction of RH with OH radicals dominates generating new intermediate radicals and accelerating ozone production. The later scenario is more plausible in an industrial zone with solvent extraction units resulting in higher VOC emissions than NO_x.

Another important species with complex chemical structure is the particulate matter (PM). Though it represented as one species, the dispersion characteristics of PM vary depending on the size of the particles. Particles suspended in the air are classified by size (aerodynamic diameter) and chemical composition, and are classified by size into coarse, fine, and ultrafine particles (**Figure 23**).

- Total suspended particulates (TSP, with aerodynamic diameter <~30 microns (μm)
- PM_{10} (with an aerodynamic diameter of less than 10 μm, also referred to as **coarse**)
- $PM_{2.5}$ (with an aerodynamic diameter of less than 2.5 μm, also referred to as **fine**)
- Ultrafine PM are those with a diameter of less than 0.1 micron

Figure 23: Particulate Size Distribution[22]



These size distinctions result because coarse and fine particles come from different sources or formation mechanisms, which lead to variation in composition and properties. The range of sizes also affects the atmospheric lifetime, spatial distribution, indoor-outdoor ratios, temporal variability, and health impacts of particles[23].

It is not possible to define a universal composition of fine and coarse particle portions that applies to all times and places. Some of these particles occur naturally, originating from volcanoes, dust storms, forest and grassland fires, living vegetation, and sea spray and some exist as a result of human activities, such as fossil fuel combustion, industrial emissions, and land use change.

PM is further classified into two categories, primary and secondary particles.

- Primary particles are emitted directly into the atmosphere from sources such as burning, industrial activities, road traffic, road dust, sea spray, and windblown soil and are composed of carbon and organic compounds, metals and metal oxides, and ions.
- Secondary particles are formed through the chemical transformation of gaseous. Gaseous pollutants such as SO_2, NO_x, certain VOC's, and Ammonia (NH_3) among others, into Sulfates, Nitrates, Secondary Organic Aerosols, and Ammonium Ions.

The secondary particles are most often part of the fine PM fraction. While modeling, the particulates are simulated as six size bins in the CHIMERE model (for regional and sub-regional scales) and as three size bins in FARM (for local and urban scales), to account for varying deposition and transport rates.

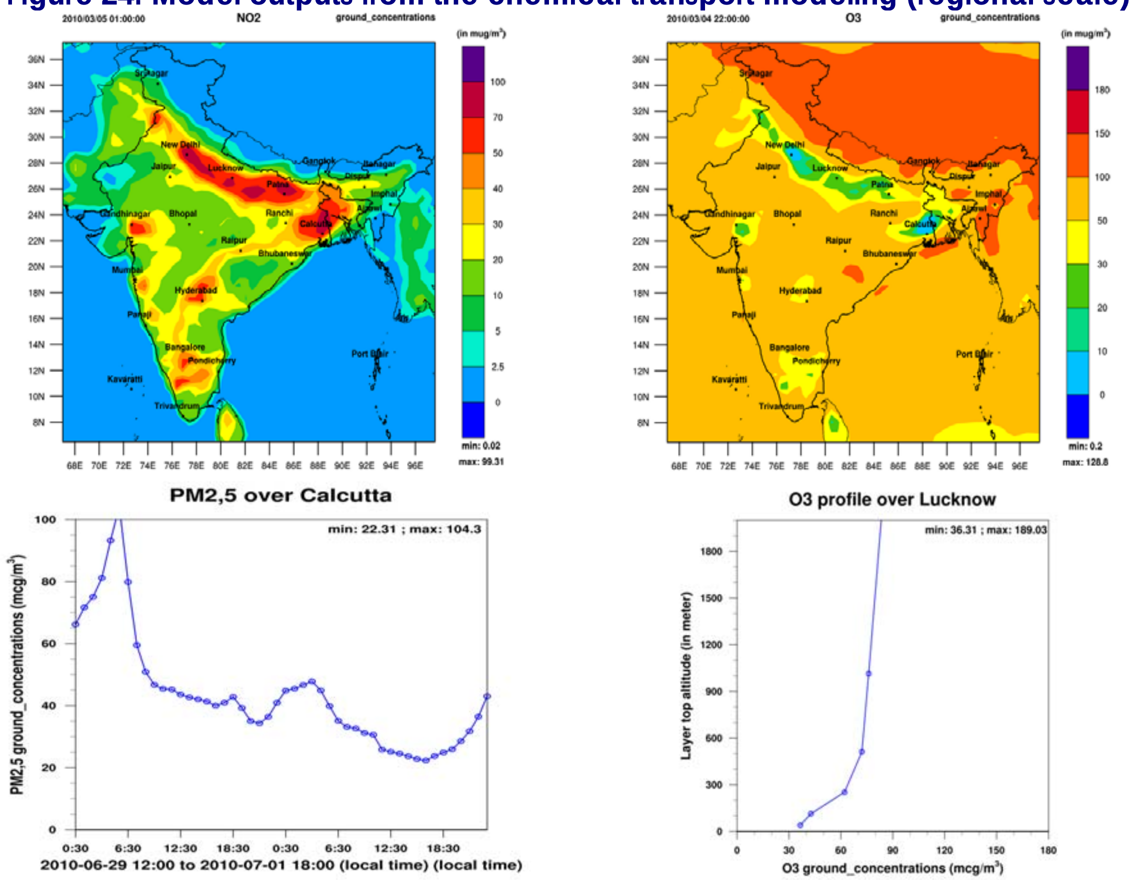
[22] Dr. Judith Chow, Desert Research Institute, Reno, NV, USA

[23] A summary of the health impacts of PM and how to estimate the health impacts is presented in SIM-air working paper No.6 @ http://www.urbanemissions.info

The Air Quality Forecast Modeling System - Outputs

The outputs for these models include geographical maps, time series and vertical profiles of pollutant concentrations at points of interest spread across the domains. Example maps for Domain 1 are presented **Figure 24** along with a time profile for $PM_{2.5}$ over Kolkata and vertical profile for Ozone over Lucknow. The profiles and time series are prepared for all the key pollutants and ~40 cities across India. The maps for all pollutants are generated at 1 hour average and 24 hr (daily) average. The later are utilized to compare with the national ambient standards[24]. It is important to note that at this scale of modeling, the cities are represented at boxes and the values represent an average for the entire city.

Figure 24: Model outputs from the chemical transport modeling (regional scale)

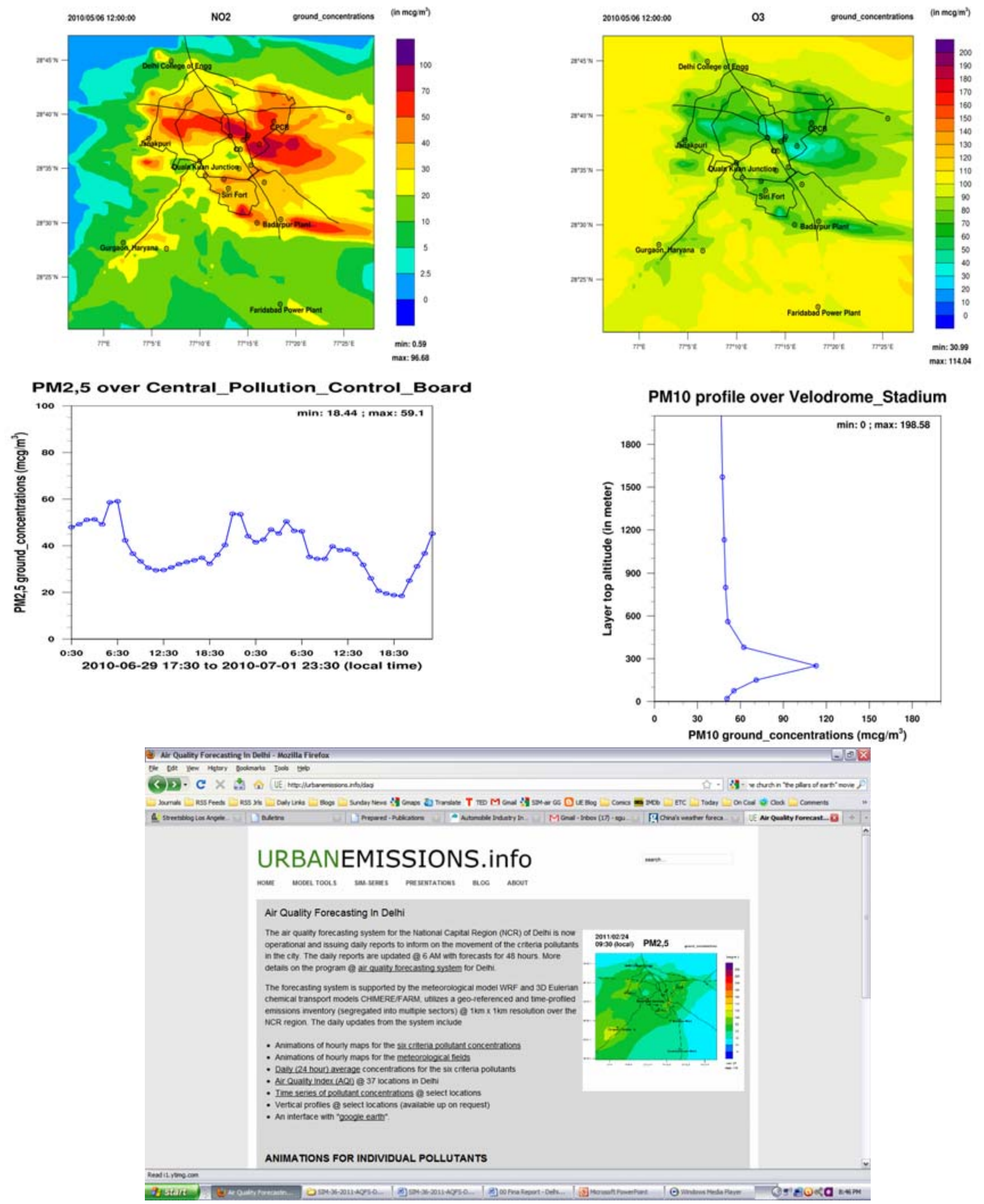


Similarly, outputs for Domain 4 (NCR) are presented in **Figure 25**. Unlike the regional scale model results, the time series and the vertical profiles here represent values from 1km x 1km grid box for the points of interest. The time series and vertical profiles are extracted for all the monitoring sites, historical sites (such as India Gate), the Commonwealth Games venues (including Games village) and the CPCB. At the urban scale, where the health impacts are felt the highest and given the detail on information (following the road corridors and the power plant plumes) the greater details in the emissions and their profiles are clearly

[24] National ambient air quality standards for India
@ http://cpcb.nic.in/National_Ambient_Air_Quality_Standards.php

visible, along with the diurnal cycles (for pollutants like ozone). In **Figure 25**, the impact of the Badarpur power plant is clearly visible as a plume (traverses to the east) and the affect of the traffic flow along the Delhi-Gurgaon corridor on May 26th, 2010.

Figure 25: Model outputs from the chemical transport modeling (urban scale)



The model results are also interfaced with animation tools, which allow the user to study the flow of pollution in 3-dimensions.

Dissemination of Air Quality Information

The single most important policy support provided by an operational air quality forecasting system is public awareness. With the growing air pollution problems, the reduction of health risks is top priority and a forecast system (in conjunction with monitoring data) can provide the necessary support to avoid the exposure risks.

In general, the policy decisions (short term and long term) are based on the monitoring data and recently, the modeling efforts are gaining ground. For example, before and during the 2008 Olympic Games, the air quality in Beijing was at critical stages. A number of interventions were introduced 2 months prior to the games, such as restricting half of city's personal vehicles and shutting down a number of industries, not only in Beijing, but also in the neighboring cities[25]. While these decisions were partly in conjunction with the monitoring data, the "*what if*" scenario analysis and a real time forecasting system played a crucial role in designing these interventions.

The air quality forecasting systems, established and operational in United States[26], Canada, and Europe, provides a vehicle to not only inform the public about the risks of possible air pollution exposures, but also use the assimilated data for policy analysis of the future scenarios.

Typically, the pollution is presented as air quality index (AQI), while the absolute numbers are used for further analysis. The AQI is an "index" determined by calculating the degree of pollution at various locations in the city and includes five main pollutants – PM, SO_2, NO_x, Ozone, and CO. The methodology is customized and changes from country to country depending on the national ambient standards. In numbers, AQI is represented between 0 to 500 with 0 representing good air and 500 representing hazardous air. For better understanding and presentation, the AQI is broken down into six categories, each color coded with the number scale.

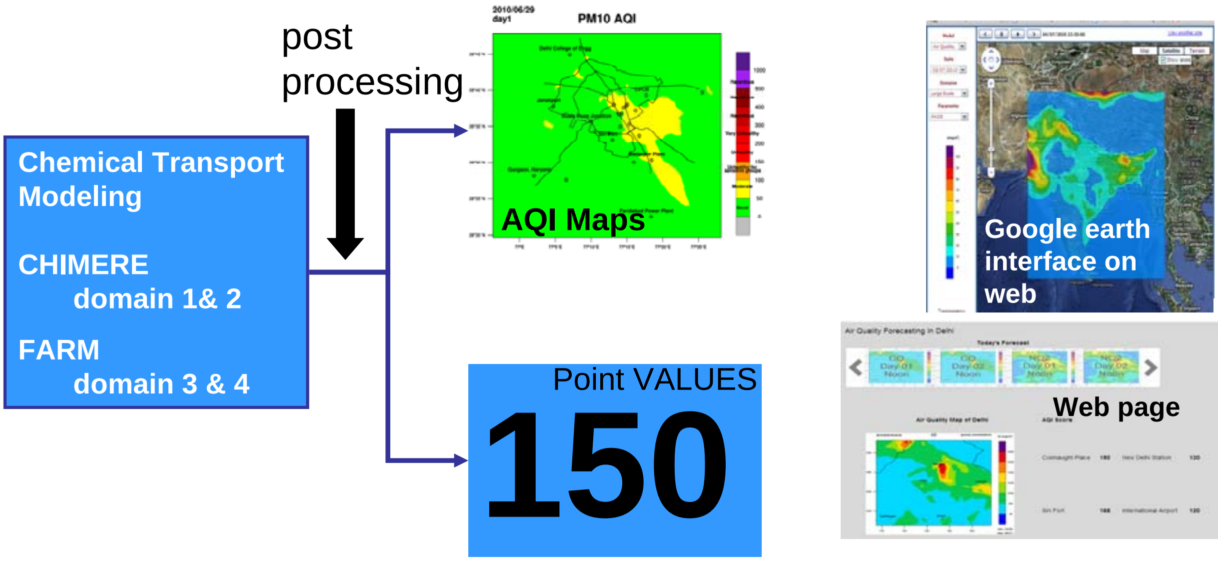
Table 2: The AQI color codes and their definitions

0-50	"**HEALTHY**" – this range poses little or no risk to the general public. No cautionary actions are prescribed.	51-100	"**MODERATE**" - is acceptable for general public. However, unusually sensitive people should be cautious.
101-150	"**UNHEALTHY**" - is borderline unhealthy, particularly for members of sensitive groups.	151-200	"**UNHEALTHY**" - is considered unhealthy for most of the public where everyone may begin to experience some discomfort.
201-300	"**VERY UNHEALTHY**" - can trigger a health alert, meaning everyone may experience more serious health effects.	>300	"**HAZARDOUS**" – this range triggers health warnings under emergency conditions, affecting all age groups.

[25] Science Daily, "Olympic Pollution Controls In Beijing, China, Had Big Impact On Air Pollution Levels", December 19th, 2008, @ http://www.sciencedaily.com/releases/2008/12/081216131016.htm
A summary of the air pollution reductions efforts is provided by the Clean Air Initiative for Asian Cities @ http://www.cleanairnet.org/caiasia/1412/article-72720.html
[26] The AQI for United States is available @ www.airnow.gov and more examples for cities across the world are @ http://urbanemissions.blogspot.com/2009/02/air-quality-index-aqi-in-urban-centers.html

For the air quality forecasting system in Delhi, the AQI is calculated for the entire domain and presented as a map for each hour and daily average (**Figure 26**). For convenience, the results are also extracted for the points of interest, similar to the time series and vertical profiles for various pollutants, and summarized as values, which can be disseminated to the public, media, and other agencies more conveniently.

Figure 26: Model configuration of post-processing for information dissemination

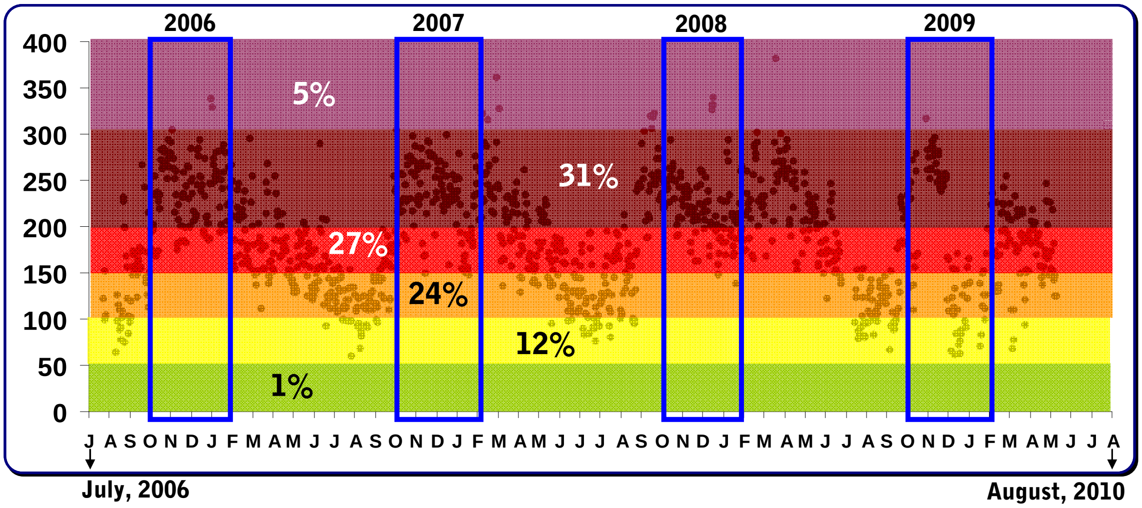


A methodology developed for the city of Delhi was employed to analyze AQI based on the monitoring data from six stations across Delhi[27]. The results are summarized in **Figure 22**, highlighting the winter months with a blue box for each year. The winter months experience the worst pollution each year starting in October and leading in to February, the following year. Other observations -

- The **Figure 27** also presents the percentage of each color code estimated, based on the average AQI. At the monitoring sites, AQI is often worse than the health standard of 150. On an average only 37% of the days between July 2006 and August 2010 was calculated with AQI less than 150.
- In **Figure 27**, the winter months are highlighted with a blue box for each year. The winter months experience the worst pollution starting in October and leading into February, the following year.
- The AQI's greater than 300 are most often associated with the winter season.
- The pollution levels are particularly enhanced in the winter months due to inversion and higher amounts of biomass usage for heating purposes (a low lying source, which tends to disperse less under low inversion conditions).
- The worst is observed in the winter months and the best during the monsoon months of July and August.

[27] For reference, see the SIM-air working paper No.35, "Air Quality Index (AQI) for Delhi, India: Trend Analysis & Implications for the CWG 2010 and Beyond" @ http://www.urbanemissions.info

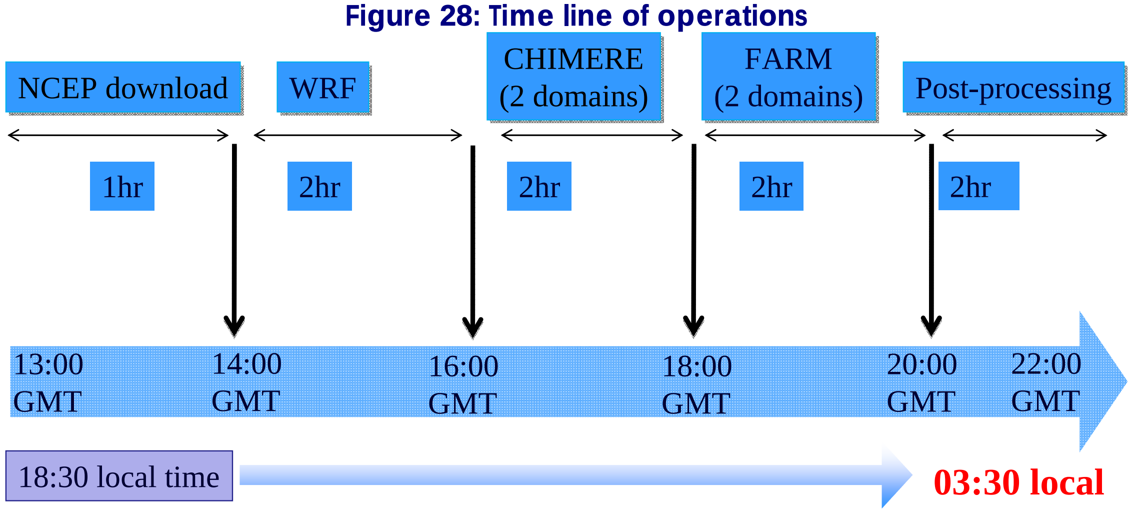
Figure 27: AQI based on $PM_{2.5}$ measurements @ ITO monitoring station



In Conclusion

The air quality forecasting is data intensive, computationally challenging, and requires multiple hours to generate the information that can be sensibly distributed among various stakeholders, either for awareness or for public policy dialogue, or for studying an academic question, such as the role of the power plant emissions on local and regional air quality or the health benefits of converting the diesel buses to CNG on a mass scale, as it was achieved in Delhi in early 2000s. The **Figure 28** presents the time line of the calculations in case of the air quality forecasting system based on a server with 12 CPUs (and 24 threads).

Figure 28: Time line of operations



The forecasting system was used as one of the tools to support the process of information dissemination to the media and the athletes during the 2010 Commonwealth Games and now in operation at the Central Pollution Control Board, New Delhi, India.