GAW Report No. 217

System of Air Quality Forecasting and Research

(SAFAR - India)

World Meteorological Organization
Weather • Climate • Water

GLOBAL ATMOSPHERE WATCH

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WORLD METEOROLOGICAL ORGANIZATION

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SYSTEM OF AIR QUALITY FORECASTING AND RESEARCH (SAFAR-INDIA)

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EXECUTIVE SUMMARY

When local concentrations of air pollutants exceed certain threshold limits, this can have adverse effects on the health of human beings, plants and animals. Advance information on air quality along with weather information can greatly benefit citizens in planning their activities and preventing themselves from those adverse effects. This is the motivation for SAFAR.

Air is a mixture of various gases, important for survival of the human race and life on the Earth. In a fixed proportion it's a life supporting system, but if the composition of air alters by the increase of what are called criteria pollutants, this can lead to detrimental effects on the health of humans and the environment. These pollutants include trace gases such as ozone (O_3), carbon monoxide (CO), sulphur dioxide (SO_2), nitrogen dioxide (NO_2), and particulate matter (PM)(PM_{10}: particles having size less than 10 µm; $PM_{2.5}$: particles having size less than 2.5 µm). Deteriorating air quality is one of the biggest challenges in the world. Several studies have proved that deteriorated air quality is associated with increased health problems resulting in increased hospital admissions due to cardiovascular and respiratory disorders. A recent study conducted on 10 000 healthy individuals in several Indian cities by Dr Sundeep Salvi et al. (Chest Research Foundation, Pune) reported that Indians have 30% lower lung function compared to Europeans, the reason is attributed to air pollution. In addition, elevated concentrations of methane (CH4), carbon dioxide (CO_2), black carbon (BC), and organic carbon (OC) have potential to change the Earth's heat balance and can lead to global warming or cooling.

In view of the current scenario of the air pollution problem and targeting the need to address this, the Indian Ministry of Earth Sciences (MoES) has sponsored an ambitious project System of Air Quality and Weather Forecasting and Research (SAFAR), which has been conceived, developed and implemented by the Indian Institute of Tropical Meteorology (IITM, MoES), Pune, in collaboration with relevant institutes in India and international experts and has been adopted as a pilot project of the World Meteorological Organization (WMO). It has been the understanding that after the implementation and successful running for one year the city specific system will be handed over to the India Meteorology Department (IMD) for routine operational forecasting whereas the frontline research work will continue to be carried out jointly by IITM and IMD. The first Indian air quality forecasting system SAFAR has been developed for the capital city Delhi for the Commonwealth Games held in 2010, to provide location specific air quality and weather forecasts 1-3 days in advance along with associated advisories. Considering that India has successfully demonstrated and established the SAFAR system in Delhi, WMO has further taken up SAFAR pilot projects for other major metropolitan cities in India. This system has been implemented in Pune in 2013.

The SAFAR project involves establishing a dense observing network, forecasting and modelling on super computers, and emission inventory preparations. Thereafter planning for dissemination of information in the form of LED displays, SMS alerts, IVR-services and live web portal has been included. The SAFAR network of Air Quality Monitoring System (AQMS) and Automatic Weather Stations (AWS) established within city limits represents selected microenvironments. Data from one station cannot be representative of the entire city, it could even mislead, as it may be biased towards a particular activity or environment. As per guidelines provided by us, the way to determine a single index for the air quality of a city is to consider different microenvironments. Hence, based on scientific knowledge, IITM has developed the guidelines for the same. City background, commercial, urban complex, sub-urban, residential, industrial, road side, traffic junction, etc. are the microenvironments which have been covered in the SAFAR monitoring network.

The online sophisticated US-EPA approved instruments simultaneously monitor a range of pollutants including PM_{10}, $PM_{2.5}$, PM1, ozone, CO, NOx (NO, NO_2), BC, methane, non-methane hydrocarbons, VOCs, benzene, and mercury, along with meteorological parameters, including temperature, humidity, wind speed, wind direction, solar and UV radiation. The near-real-time

online raw data is then transferred to the SAFAR control room through GPRS at 15 min intervals and validated by an expert scientific team. Another major aspect of reporting air quality is data quality. Rigorous quality control and quality checks should be made before releasing the data to officials and the public as very important decisions may be taken on the basis of these values.

Pollutants are added to the environment through emissions of various natural as well as anthropogenic sources. Thus SAFAR also prepared a national report wherein a baseline gridded emission inventory was developed for India, which may be useful in addition to providing for relevant information for air quality purposes for providing more realistic Indian input in global climate models for improved simulations.

The other aspect of the project, besides the technical one, is communication with the public. The SAFAR system provides information on current and 1-3 days advance forecast for air quality and weather, on harmful radiation and the emission scenario over the city area in a simple and user-friendly format. The location specific products of the system include Air Quality- Now, Air Quality-Tomorrow, Weather-Now, Weather-Tomorrow, UV Index - Skin Advisory, AQI - Health Advisory and City Pollution Maps. An Air Quality Index (AQI) is a rating scale used for reporting the quality of air as a public information tool that helps protect public health. The UV Index is a measure of the intensity of UV radiation expected to reach the earth's surface, reported at least for the daily maximum value. It is an indicator of the potential for skin damage and can alert people to adopt protective measures when exposed to UV.

To disseminate the information to a maximum, stakeholder user-friendly platforms have been developed where one can access the products easily, these include a dynamic professional web portal (http://safar.tropmet.res.in/), a LED- Digital Display Board System (DDS), and an Integrated Voice Response Service (IVRS) (Toll free No: +91- 1800 1801 717). The information is updated at each hour to note the variability and to provide the most current air quality and weather conditions. The public may subscribe to the Alert Network through the website to receive direct E-mail or SMS alerts for extreme weather conditions or an air pollution event. All these facilities are available in English, Hindi and the regional language. Those interested in information by e-mail, can also contact safar@tropmet.res.in. A new digital concept has been developed within SAFAR which is called “AWADHI” (Air Quality and Weather- Assessment and Data on Hi-Tech-Digital India), a one stop shop for Metro air quality and weather information for all SAFAR stations in the country on digital media located in the IITM, Pune, control room that caters to all information.

The SAFAR system is depicted in Figure 1 and the stakeholders and beneficiaries in Figure 2.

During the coming years India has planned to develop similar systems for other metropolitan cities including Chennai, Hyderabad, Kolkata, Ahmedabad, whereas the work is in progress for Mumbai. SAFAR is a good example of how science can be used for improving living standards and quality, and for the benefit of people, as by using such a system adverse health impacts and environmental deterioration can be decreased. We should not forget that air is an essential component of human life on which all living things depend for survival and it is our duty to keep it clean and healthy. Our vision is to provide authentic air quality data to the public along with its 1 to 3 days advance forecast in a very simple and user-friendly format. This early warning system will help the public in reducing the burden of disease by taking precautionary measures. The system is useful for various sectors including health, agriculture, aviation activity, urban planning and urban development, disaster management and tourism. This early warning system provides products, which are of economic value, and helps to improve awareness and to implement air quality management programmes to reduce emissions of various air pollutants. It will ultimately aid in achieving faster, more inclusive and sustainable growth to which India has committed during the 12^{th} five year plan (2012-17), helping to reduce the total cost of environmental damage caused by air pollution.

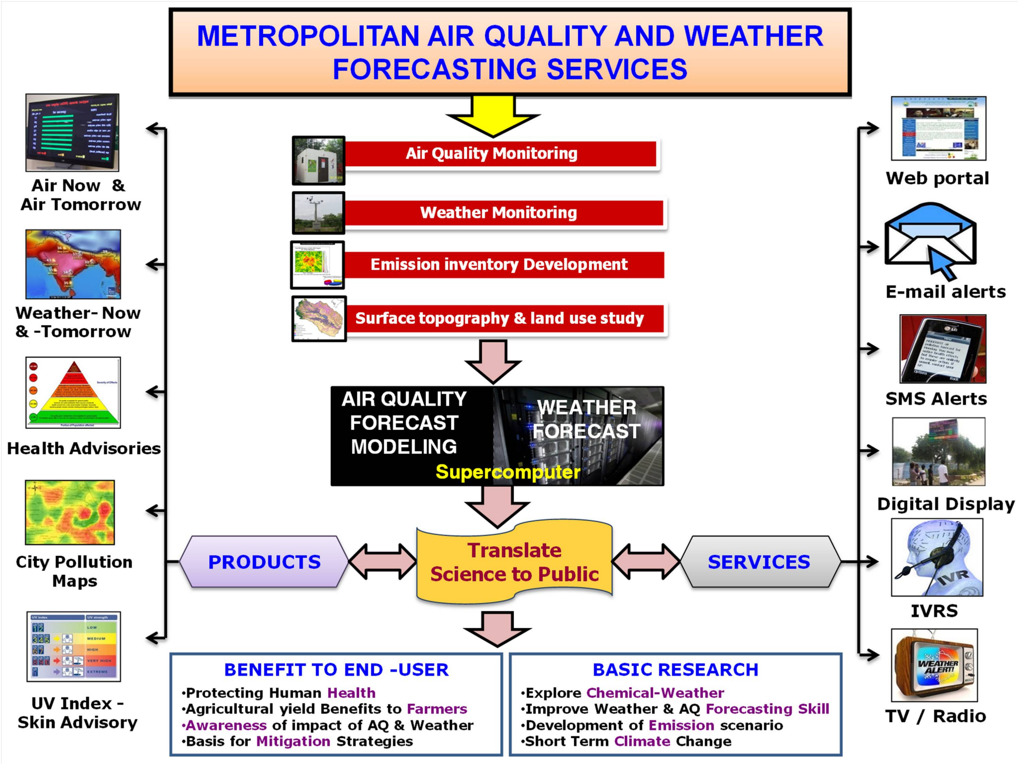


Figure 1. SAFAR at a glance: Left to right column: (1) SAFAR generated products; (2) Developmental flow and (3) Tools for information dissemination

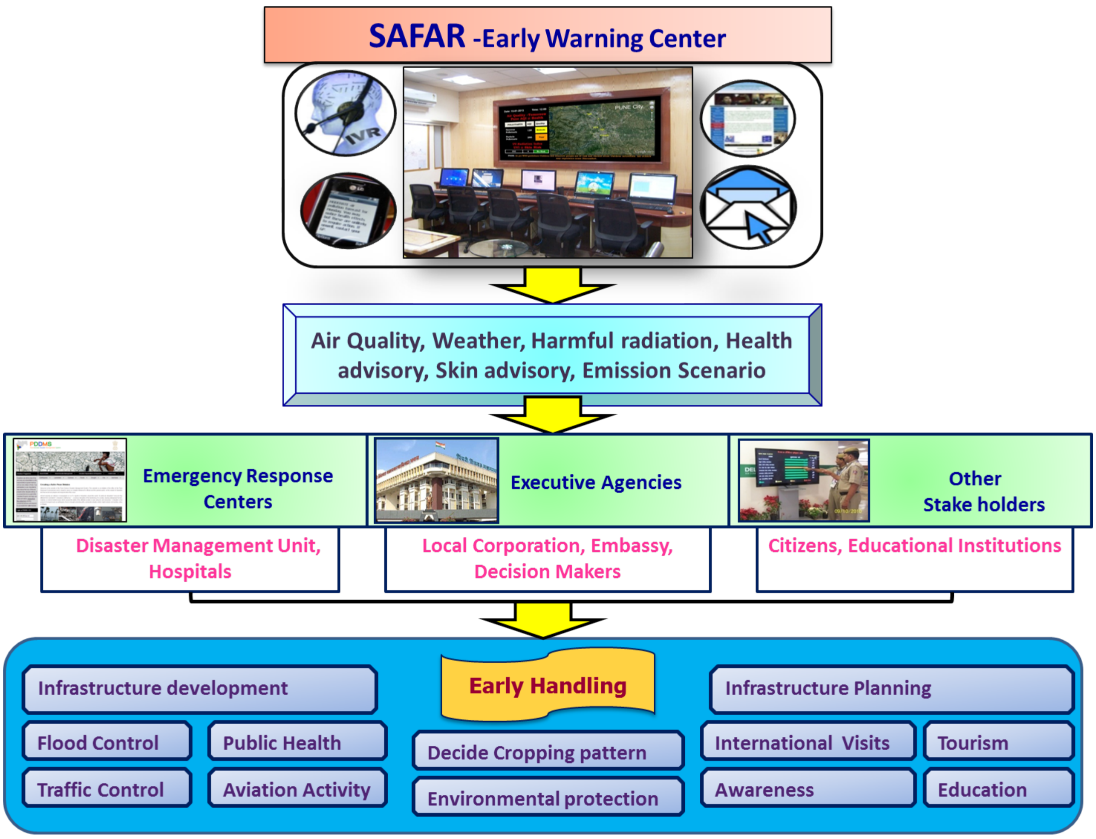


Figure 2. SAFAR stakeholders and beneficiaries

1. ATMOSPHERIC POLLUTANTS AND THEIR HEALTH EFFECTS

Clean air is a basic necessity for human health and well-being. According to the World Health Organization (WHO), metropolitan cities are critically affected by atmospheric pollution. Rapidly developing metropolitan cities of India are on top of the Indian map in terms of pollution. The public health impacts of air pollution can be classified in two categories namely (a) acute and (b) chronic health outcomes, due to exposures to particulate and gaseous air pollutants, which can be assessed by evaluating mortality rate, hospital admissions, and other clinically significant health indicators. Exposure to air pollutants can cause a range of symptoms. People with lung or heart disease may experience increased frequency and/or severity of symptoms, and more medication requirements. Of course, each individual will react differently to air pollution, depending on the type of pollutant a person is exposed to, the degree of exposure, the individual's health status (immunity) and genetics. Negative health effects increase as air pollution worsens. During a high pollution episode, healthy people may show more resistance than an individual suffering from a pre-existing health problem. Studies have shown that even modest increase in air pollution for a short period can cause a small but measurable increase in emergency room visits and hospital admissions among sensitive or at-risk people, while healthy individuals may not show any effects. On the other hand, also healthy people, especially those who work or exercise outside, are affected by air pollution (Avol et al. 1998; Delfino et al. 1998; Wong et al. 2002; Katsouyanni et al. 2001; Pope et al. 2002).

Most common categories of people at high risk are the people who have acute respiratory illnesses such as asthma, chronic obstructive pulmonary disease (COPD), chronic bronchitis and emphysema or lung cancer. Individuals with existing cardiovascular conditions such as angina, previous heart attack, congestive heart failure or heart rhythm problems (arrhythmia or irregular heartbeat) are sensitive to air pollution. It has been shown that there is an association between diabetes and air pollution (www.diabetesandenvironment.org/home/contam/air; Pearson et al. 2010).

High level of pollutants in the air makes breathing difficult which in turn triggers the early onset lung and heart- related symptoms. Infants and children are especially susceptible to the harmful health effects of air pollution as their body and vital organs are still at very tender stage. Children, in particular, have greater exposure to air pollution because they breathe in more air per kilogram of body weight than adults and they usually spend more time outside being active outdoors. Their elevated metabolic rate and young defence system make them more vulnerable to air pollution. Air pollution can trigger an asthmatic attack and aggravate symptoms of respiratory ailments like coughing and throat irritation even in healthy children. Elderly people also are more likely to be affected by air pollution, due to generally weaker lungs, heart and defence systems, or undiagnosed respiratory or cardiovascular health conditions. People participating in sports or strenuous work outdoors breathe more deeply and rapidly allowing more air pollutants to enter the lungs. People who are otherwise healthy may have symptoms like eye irritation, increased mucus production in the nose or throat, coughing, and difficulty in breathing especially during exercise. People with asthma or COPD may notice an increase in cough, wheezing, shortness of breath or phlegm. People with heart failure may experience increased shortness of breath or swelling in the ankles and feet and those with heart rhythm problems may notice increased fluttering in the chest and feeling light-headed. People suffering from angina or coronary artery disease may have increased chest or arm pain.

Six commonly found air pollutants in the atmosphere that carry health or performance impairment risks are carbon monoxide (CO), particulate matter (PM) ($PM_{2.5}$ category belong to particles having size less than 2.5 micrometer (μm) and PM_{10} for particles having size less than 10 μm), nitrous oxides (NO_X), sulphur dioxide (SO_2), ground-level ozone (O_3), and volatile organic compounds (VOCs). Prolonged exposure to these pollutants can cause difficulty in breathing, respiratory disease and heart disease. Regarding health effects of these pollutants the reader is referred to the information that can be found on the WHO website especially in the Factsheet on Ambient (outdoor) air quality and health (www.who.int/topics/air_pollution/en/). Figure 3 shows the complex progression involving various physical, chemical, and biological processes from emission sources to manifested health effects. Individual reactions depend on individual factors such as genetic predisposition, nutritional status, pre-existing diseases and stress.

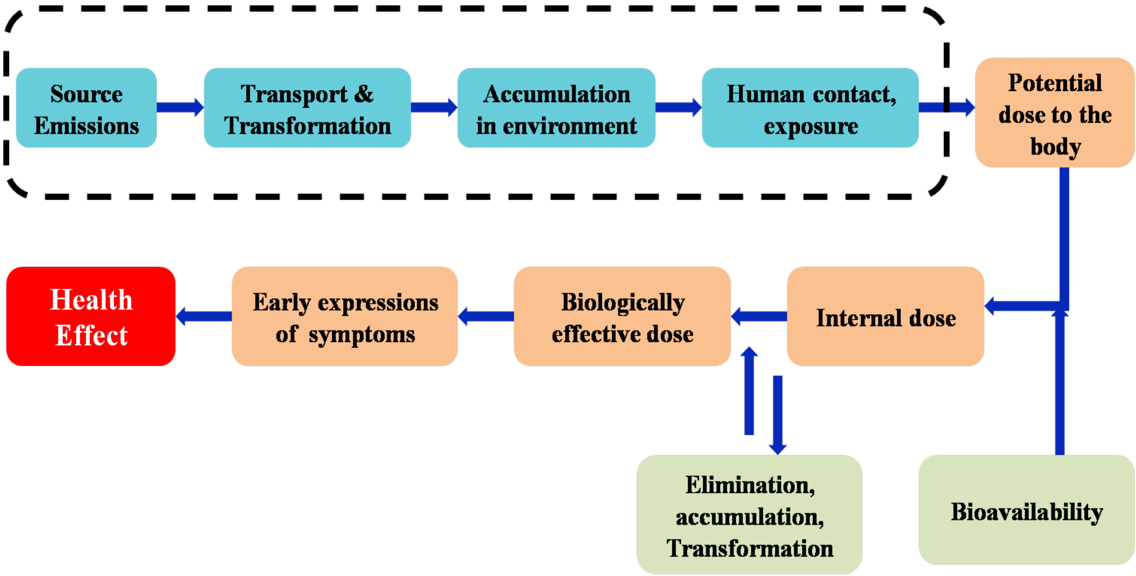


Figure 3. Health effects of air pollution

1.1 Particulate matter

Choice of an indicator for particulate matter requires a number of considerations. At present, most routine air quality monitoring systems generate data based on the measurement of PM_{10} and not on segregated data. Consequently, the majority of epidemiological studies use PM_{10} as the exposure indicator. PM_{10} represents the particle mass that enters the respiratory tract and, moreover, it includes both the coarse (particle size between 2.5 and 10 μm) and the fine particles (measuring less than 2.5 μm, $PM_{2.5}$) that are considered to contribute to the detrimental health effects observed in the urban environments. The former particles are primarily produced by mechanical processes such as construction activities, road dust-suspension and wind; whereas the latter originate primarily from combustion sources. In most urban environments, both coarse and fine mode particles are present, but the proportion of particles in these two size ranges is likely to vary substantially from one city to another around the world, depending on local geography, meteorology and specific PM sources. In some areas, the combustion of wood and other biomass fuels can be an important source of particulate air pollution, the resulting combustion particles being largely in the fine ($PM_{2.5}$) mode.

1.2 Ground level ozone

The ozone layer (layer in the upper atmosphere, i.e. in the stratosphere which contains a relatively high concentration of ozone) is beneficiary, as it absorbs 97-99% of the sun's ultraviolet radiation, which has the potential to damage life on the Earth, and hence acts as a protecting layer. But on the other hand, an abnormally high concentration of ozone in the lower atmosphere (troposphere) is considered as an air pollutant due to its adverse effect on plants and animals, including human beings. Ground level ozone harms the respiratory system of animals and burns plants, in addition to this, it is a greenhouse gas making its monitoring and study even more important. Ozone is formed in the atmosphere by photochemical reactions in the presence of sunlight and precursor pollutants nitrogen oxides (NO_X) and volatile organic compounds (VOCs). It is destroyed through chemical reactions and through dry deposition on surfaces. Several studies have shown that ozone concentrations correlate with various other toxic photochemical oxidants arising from similar sources, including peroxyacetyl nitrate, nitric acid and hydrogen peroxide. Significant additions to the health effects evidence base have come from epidemiological time-series studies. As ozone concentrations increase, health effects at the population level become increasingly numerous and more severe. Such effects can occur in places where concentrations are currently high due to human activities or that are elevated during episodes of very hot weather due to increased ozone production.

1.3 Oxides of sulphur and nitrogen

Nitrogen dioxide (NO_2) and sulphur dioxide (SO_2) are bad smelling gaseous criteria pollutants. NO_2 and SO_2 are both very soluble gases that convert to nitric and sulphuric acids when they make contact with moisture, including in the moist lining of the mouth and lungs and thus they are linked with a number of adverse effects on the respiratory system.

NO_2 is generally formed due to oxidation of nitric oxide by oxygen in air. Nitrogen dioxide reactions with hydrocarbons in the presence of sunlight is the main source of tropospheric ozone, another important air pollutant, and NO_2 is also important in the formation of nitrate aerosols, which form an important fraction of the ambient air PM mass. The primary source of NO_2 is the burning of fossil fuels, thus mainly motor vehicles and power plants, and waste incineration systems.
SO_2 is produced from the burning of sulphur-containing fossil fuels (coal and oil), especially for power generation and industrial facilities. Smaller sources of SO_2 emissions include industrial processes such as extracting metal from ore, and of burning high sulphur-containing fuels by locomotives, large ships, and non-road equipment.

1.4. Carbon monoxide

Carbon monoxide (CO) is an odourless, colourless and toxic gas that results from incomplete combustion. Since it is impossible to see, taste or smell the toxic fumes, CO can kill you before you are aware of it. At lower levels of exposure, CO causes mild effects that are often mistaken for the flu. These symptoms include headache, dizziness, disorientation, nausea and fatigue. Acute effects are due to the formation of carboxyhemoglobin in the blood, which inhibits oxygen intake. Sources of CO are unvented kerosene and gas space heaters; leaking chimneys and furnaces; back-drafting from furnaces, gas water heaters, wood stoves, and fireplaces; gas stoves; generators and other gasoline powered equipment; automobile exhaust and tobacco smoke. Worn out or poorly adjusted and maintained combustion devices (e.g. boilers, furnaces) can be significant sources, as can be car, truck, or bus exhausts from garages, nearby roads, or parking areas. It may be fatal at very high concentrations. Moderate concentrations may cause angina, impaired vision, and reduced brain function.

2. EVOLUTION OF SAFAR

Recognizing air quality as already a problem in Delhi, with the initiative by the Ministry of Earth Sciences (MoES), India, responsibility was given to IITM to develop related appropriate services for the public and decisionmakers for the Commonwealth Games in 2010 (CWG-2010). This became a WMO Global Atmosphere Watch (GAW) Urban Research Meteorology and Environment (GURME) pilot project. In view of the successful implementation of SAFAR in both operational and research modes, it was recommended to be replicated and implemented in Delhi and in five more Indian metropolitan cities, namely Pune, Mumbai, Chennai, Kolkata, and Ahmadabad under the ministry's 12^{th} 5-year plan scheme "Metropolitan Advisories for Cities for Sports, Tourism (Metropolitan Air Quality and Weather Services)". It is expected that SAFAR could set an example for developing countries.

The capital of India, New Delhi is among the most populated cities in the world. Rapid and unplanned urban development along with unprecedented population growth has lead to relentless increase in air pollution in this megacity. Almost all the major anthropogenic sources such as coal based thermal power plants, large number of industries and high vehicular density exist in this city and are becoming more intensified. Besides these anthropogenic sources, the climatic conditions of Delhi such as lower temperatures, calm conditions, lower mixing height and temperature inversions during winter restrict and confine pollutant dispersion and dispersal which builds up extremely high levels of pollutants in the air. Frequent dust storms are a problem in summer. Seeing that CWG 2010 was held in Delhi in the month of October, air quality monitoring and forecasting, especially during the Games, was high on the list of priorities so that steps to improve the ambient air quality within the city could be taken and the health related risks of the participants and the local communities associated with the air pollution could be reduced. For a better understanding of ambient air quality in Delhi and its forecasting, an accurate estimation of anthropogenic emissions of the air pollutants is of great significance, as the quality of forecasting depends on the accuracy and reliability of estimation. As discussed earlier, air pollutants that are emitted into the atmosphere as a result of variety of individual sources and processes have a large spatial and temporal variability. It is impractical to measure each emission source individually continuously. In such circumstances, an emission inventory (EI) is the best tool to tackle the problem efficiently.

An emission inventory is a comprehensive listing of sources of air pollutant emissions and amounts of air pollutants released into the air as a result of a specific anthropogenic or natural process in a particular geographic region during a specific time period. It has been used as one of the important fundamental components in air quality modelling applications and also for air quality management plans to measure progress/changes over time to achieve cleaner air. For scientific purposes, emission inventories can be used as an input to 3D atmospheric chemical transport models that are aimed at understanding the chemical and physical processes and the behaviour of air pollutants in the atmosphere and for forecasting. Apart from scientific application, emission inventories could be used for formulating environmental policies and legislation. At present, there are many emission inventories available for Delhi, but they have certain limitations in one way or other and are focused on a specific sector or objective. To our knowledge none of these inventories covers as much of Delhi and its surrounding region as is accounted for in the SAFAR-Delhi as an essential component of the atmospheric chemical transport modelling.

Organizational structures like the Central Pollution Control Board (CPCB), the National Environmental Engineering Research Institute (NEERI), Indian Institute of Technology, Delhi, (IIT, Delhi), Indian Institute of Science (IISc) and Indian Oil Corporation Ltd. (IOCL) either independently or in collaboration with each other have developed such kind of EI's for Delhi. CPCB along with NEERI carried outsource apportionment studies in Delhi. These studies identified some primary and secondary areas of emission hotspots. They revealed that vehicles are the major contributors of air pollutants followed by coal based thermal power plants. Residential and commercial sectors also contribute considerably to the total emissions of air pollutants in Delhi. The pollutants considered in these studies were the criteria gases, hydrocarbons (HC), and PM.

Most of these studies focus on the transport sector alone. Information regarding emissions from industries is limited, moreover these studies are restricted to the city areas only. As far as the national capital territory (NCT) is concerned, no elaborate studies have been carried out. In most of the cases, emission inventories are developed for older periods and do not include the latest emission status of Delhi. The development of an emission inventory is one of the critical and most sensitive elements for a modelling study to forecast air quality and should be as recent as possible. These studies were not up to date and did not cover the entire NCT region. Moreover, available estimations were done mainly at gross level and not gridded as finely as required for forecasting models and hence the task remained unfulfilled.

A detailed scientific study must be carried out to know the current pollutant levels and for a 1-3 days advance forecast, which can aid the policy makers for decisionmaking specifically so that required mitigation measures can be planned. In SAFAR, such an air quality monitoring and forecasting system has been launched for the first time in South Asia.

The SAFAR system was launched at the 19th Commonwealth Games hosted by India, from 3-14 October, 2010 in New Delhi by MoES in association with the Organizing Committee of the Commonwealth Games. These games were declared as the first evergreen Commonwealth games. The project provided information concerning now-cast and 24-72 hour forecast in advance for pollutants like ozone, nitrogen oxides, carbon monoxide, particulate matters <2.5μm ($PM_{2.5}$) and < 10μm (PM_{10}), benzene, toluene, xylene and BC in addition to weather services. The prior knowledge of these parameters seems to have been of great assistance for organizers, managers and athletes for efficient preparation and planning. One of the major objectives of this project was to create awareness among the general public regarding the air quality of Delhi and also to ultimately contribute towards the mitigation measures and betterment of the air quality.

This is for the first time that India had a system for air quality forecasting and New Delhi became the first city in the country to provide 24-72 hour advance forecasts for criteria pollutants. Today India is among the few developing nations to have taken a big leap in this area of environmental research. MoES has set up 10 air quality monitoring stations and 35 automatic weather stations in NCT along with GPS observations and Doppler Weather Radar. To realize the commitment of hosting the CWG by the organizing committee, MoES made elaborate arrangements to monitor, forecast and showcase the air quality and weather information in several locations in Delhi covering most of the competition venues prior to and during the games. This system was dedicated to the nation by Dr Shailesh Nayak, Secretary, Ministry of Earth Sciences, Govt. of India at the Jawaharlal Lal Nehru Sports Complex, New Delhi.

3. OBJECTIVES OF SAFAR

The objectives of SAFAR are:

(a) To develop a System of Air Quality Forecasting and Research (SAFAR) in major metropolitan cities of India (including Delhi, Pune, Chennai, Kolkata, Mumbai, Bangalore, Hyderabad) under the studies of atmospheric chemistry and climate.
(b) Monitor current status of ambient air quality, weather conditions and develop technology to forecast it 1 to 3 days in advance at city level.
(c) Study the adverse impact of deteriorating air quality on health and agriculture.
(d) Display the data, related advisories, and precautionary actions across the city to spread awareness and take preventive steps.
(e) To obtain the knowledge and understanding necessary for developing preventive and corrective measures for better health and food security leading to nation's GDP growth.

4. CONCEPTUAL FRAMEWORK OF SAFAR

The SAFAR project involves four components to facilitate the current and advance forecasting, namely:

(1) Development of the high-resolution emission inventory of air pollutants for NCT. This is a key input for the forecasting model.
(2) Establishment of a network of Air Quality Monitoring Stations (AQMS) equipped with Automatic Weather Stations (AWS) to monitor and provide air pollutant information and weather parameters 24x7 over Delhi. The continuous data monitoring has a vital role in validation of model output and data assimilation.

(3) The 3-D atmospheric chemistry transport forecasting model coupled with weather forecasting model to provide 24-72 hour advance forecast of air quality. Weather plays a major role in the transport of pollutants from the sources to other places.

(4) Dissemination of the information and reaching the general public. The data is strictly quality assured and controlled before dissemination. It is translated into a public friendly format by defining an air quality index (AQI) for India and then displayed via a network of display stations having LED and LCD screens located at different locations in Delhi. Also health advisories along with AQI are given and emergency alerts are provided to the public using different media services. Once the system is in place and has started to deliver the products, there must be a mechanism to convey the information to stakeholders, disaster management authorities and citizens for their benefits. This will help to bring awareness regarding the air quality in their city to the public and will empower them to take preventive measures to protect themselves from air pollution. In a long run, it will lead to firm up the mitigation strategies to protect human health.

Along with the pollutant information, weather information, including temperature, humidity, wind speed and wind direction, is provided for the following three products:

(1) Weather-Now: For near-real-time weather information
(2) Weather Now-casting: To provide 3-hours advance forecast using DWR, satellites, etc.
(3) Numerical weather forecast model to provide 24-72 hours advance forecast.

The data collected from the monitoring network is a major input for the forecasting model along with the results of the emission inventory. After running the 3D atmospheric chemistry transport model with such valuable inputs, results are transferred to the IITM Data server. Once the near-real-time and forecasted data is checked for quality assurance, it is transferred to the display server for converting to public friendly format in terms of the AQI. AQI is used to represent the current pollutant levels in easily understandable formats using colour codes, and a numerical range with associated health impacts. The AQI is calculated as per the latest standards released for India. Once it is done, it is available for the common public through a network of LED and LCD digital display boards installed at 12 different locations in the national capital region (NCR). Environmentally friendly messages along with the advisory on how to keep the environment clean are also displayed on the display boards. In addition, the current and forecasted AQI is made available online on the SAFAR website and conveyed by media, SMS, e-mail alert services, IVRS system, etc. The framework is depicted in Figure 4.

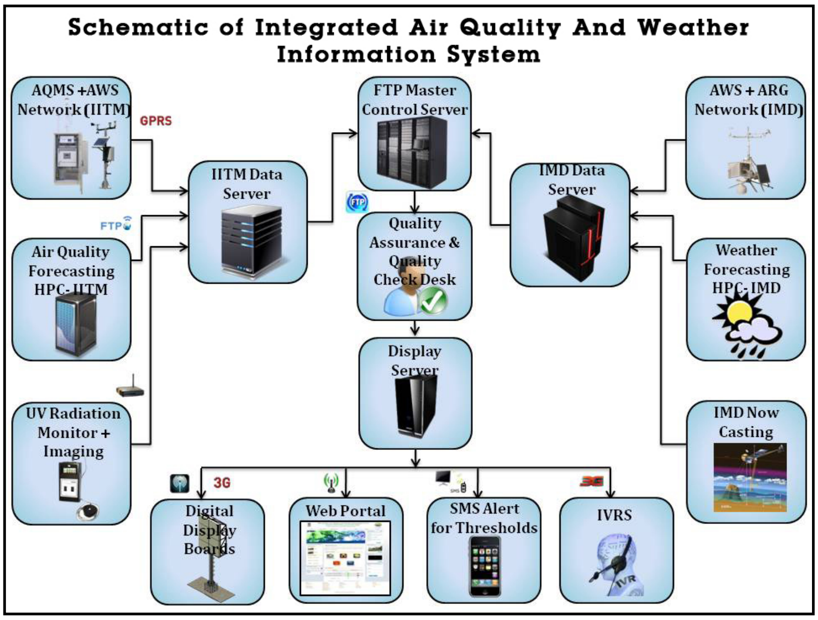


Figure 4. Framework of SAFAR

5. DEFINING AQI FOR INDIA

Very few of us pay attention to the air that we breathe, and it's quality, as we in normal circumstances cannot see and do not know what we are inhaling with around 28,000 breaths per day, and we are unaware of what we are taking in with around 10,000 litres of air in a single day. During pollution episodes the visibility can be drastically reduced and on these occasions it is usually clear that there is a problem with air quality. Thus it is extremely vital that real time air pollution information reaches the public so that they can safeguard themselves from the affects.

AQI is a scale designed as a highly useful tool for the better understanding of air around us and for connecting air quality to health. AQI serves as a protection alarming tool so an individual can protect him-/herself from air pollution by limiting to short-term exposure to air pollution and adjusting one's activities during increased levels of air pollution. Special precautionary measures are provided for the sensitive groups of population since they are at higher risk for being affected. The AQI reports current air quality based on a specific level of an individual air pollutant. The AQI communicates primarily a number from 1 to 500 indicating the quality of the air. The higher the number, the greater the health risk associated with the air quality. When the level of air pollution is very high, the number will be above 400.

Though the Indian government provided the Ambient Air Quality Standards (AAQS) for India, which were revised in 2009, the most challenging task has been to define the AQI so that the common public can understand the severity of pollution and can take adequate preventive measures to protect their health. This task has been accomplished under the SAFAR project in 2010.

5.1 A brief overview of epidemiological studies for India

All India Institute of Medical Sciences (AIIMS) has studied the correlation of outdoor air pollution and emergency visits during 1997-98 (Parivesh, 2001). The CPCB, Delhi, and AIIMS, Delhi, conducted a health survey during 1997 and 1998 on individuals residing in areas of Delhi. Emergency visits of asthma, chronic obstructive airways disease, and acute coronary events increased by 21.3%, 24.9% and 24.3%, respectively, on account of higher acceptable level of air pollutants (Parivesh, 2001). A study conducted by the Lakeside Medical Center, Bangalore, during 2001 reported that children and policemen are most susceptible to air pollution. The school going children belonging to low-income status, living near heavy traffic regions showed higher percentage of asthma as compared to children living in an area with less traffic. Traffic police showed a higher percentage of asthma than non-traffic police (Action Plan 2003 for Bangalore).

To investigate the impacts of air pollutants on the Kolkata population, CNCI Kolkata, University of Calcutta, and Department of Environment of the West Bengal government jointly conducted a study during 1996-2001. The observation and inference of the study clearly indicate that the lungs of the Kolkata population are highly burdened with respirable particulate matter with suggestive indication of inflammatory and allergic lung response and microscopic hemorrhage of lung. The study demonstrated a direct relationship between status of air pollution and, alveolar macrophage response (Lahiri et al. 2000). Brandon and Hommann (1995) extrapolated dose-response functions from developed countries to estimate mortality and morbidity due to ambient air quality exceeding WHO's guidelines in 36 cities, including Delhi. The pollutants considered were PM, SO_2, NO_X and lead. They estimated that over 40,000 premature deaths would be avoided if pollution levels in these cities were reduced to the WHO annual average standard. According to the study Delhi alone accounts for 7,500 or almost a fifth of these premature deaths. In a comprehensive study carried out by the CPCB in 2008 the association between air pollution and related adverse health effects were assessed. Results showed that individuals residing in Delhi are much worse affected due to air pollution compared to the rural control population. Lung function was reduced significantly among 40.3% of individuals in Delhi compared to 20.1% in the rural control group. Also the occurrence of asthma and visits to a hospital for respiratory problems were much higher among individuals from Delhi. (CPCB, 2008).

There are numerous epidemiological studies carried out all over the world and these studies have efficiently analyzed the strong linkup between air pollution and health effects. Most of the research highlights that individuals dwelling in cities are exposed more to air pollution in comparison to individuals living in rural areas. The very obvious reason behind this is that metro cities have faced rapid development, increased vehicular number, industrial development and population growth. The worrisome fact is that this progression of cities atmosphere is increasing. Therefore, air pollution and its health effects have now become a central point of research all over the world.

5.2 Linkages of air quality and health - Indian perspective

Urban regions in India areas are dominated by the transport sector for emissions, while in rural areas the domestic/residential wood combustion/cooking are major emission sources (Dalvi et al. 2006; Ghude et al. 2008; Sahu et al. 2008). Major pollution events are caused by wild fires, fire management burns and dust storms. The frequency of air pollution episodes are likely to peak in India during El Nino years when the Indian monsoonal rainfall is most likely to be poor causing dry environment, a frequent of hot days, wild fires and dust storms. However, a wide gap exists between the atmospheric chemistry communities who are capable of providing accurate data and understand the physical and the chemical characteristics of air pollutants and medical practitioners who diagnose their impacts on human health.

The three-legged stool in the discipline of Environmental Health to study health effects caused by chemicals is epidemiology, toxicology, and exposure science. Epidemiologists assess the association of chemical exposures and health outcomes with statistics, considering other factors such as demographics and diet. The findings are evaluated /confirmed by toxicologists who search for plausible biological mechanisms of compounds in humans in the laboratories. After the toxicity of certain chemicals is confirmed, exposure scientists investigate the processes of human in contact with chemicals. Exposure science is the bridge between environment and health. It is also the field where atmospheric chemists can make significant contributions.

5.3 Role of guidelines in protecting public health

An increasing range of adverse health effects has been linked to air pollution, and at ever-lower concentrations. New studies use more refined methods and more subtle but sensitive indicators of effects, such as physiological measures (e.g. changes in lung function, inflammation markers). Various monitoring programmes have been undertaken to evaluate the quality of air by generating large amounts of data on the concentration of each air pollutant (e.g., O_3, NO_X, CO, PM) in different parts of the world. The US Environmental Protection Agency (US-EPA) is widely accepted and recognized all over the globe as giving general guidelines for providing baseline threshold limits of different air pollutants. The US-EPA designed the AQI for five major air pollutants regulated by the Clean Air Act: viz. ground-level ozone, particulate matter, carbon monoxide, sulphur dioxide, and nitrogen dioxide. For each of these pollutants, the EPA has established national air quality standards to protect public health.

5.4 National Ambient Air Quality Standards (NAAQS) for India

India has experienced a significant rise in industrial activities and vehicular growth in recent years. The increased anthropogenic activities have resulted in amplification of pollutant emissions and deterioration of environmental and human health. To assess the quality of air and to take effective steps for prevention, control and abatement of air pollution, the CPCB of the Ministry of Environment and Forest (MoEF), is executing nation-wide ambient air quality monitoring through a National Air Quality Monitoring Programme (NAMP). Several air quality standards and guidelines have been introduced by CPCB/MoEF to refer and regulate urban air quality. Of particular importance are the Air (prevention and control of pollution) Act (1981), the Environmental Protection Act (1986), the Motor Vehicles Act (1988) and the Central Motor Vehicles Rules (1989). In India ambient air quality standards were first adopted on 11 November 1982 in exercise of its jurisdiction under Section 16 (2) (h) of the Air (Prevention & Control of Pollution) Act, 1981. The air quality standards have been revised (Annexure 1) by CPCB Delhi on 11 April 1994. Different standards have been laid down for industrial, residential, and sensitive areas to protect human health and natural resources from the effects of air pollution. CPCB consulted experts in the field of air quality and health effects of air pollution to formulate the air quality standards.

The following epidemiological studies have been initiated by CPCB in India to formulate the air quality standards for the country:

(1) Epidemiological Study to find the Effect of Air Pollutants especially Respirable Suspended Particulate Matter (RSPM) and other carcinogens on Human Health in Delhi, Chittaranjan National Cancer Institute (CNCI), Kolkata.
(2) Study on Ambient Air Quality, Respiratory Symptoms and Lung Function of Children in Delhi, CNCI, Kolkata.
(3) Health Effect of Chronic Exposure to Smoke from Biomass Fuel burning in Rural Households: A Study in Northern and Eastern India, CNCI, Kolkata.
(4) Effects of Environmental Pollution on the Status of Human Health of Delhi Residents, All India Institute of Medical Sciences (AIIMS).
(5) New Delhi Human Risk Assessment Studies in Asbestos Industries in India with Industrial Toxicology Research Centre (ITRC), Lucknow.

The following approach was adopted while formulating the recent national air quality standard.

- General description of the pollutant
- Dose-response based health risk evaluation
- Current pollution levels in the country
- Current standard
- Basis of new standard and associated risk comparison
- Pollutant having long term effects should also have a 24-h standard along with the annual standard
- Dose response relationship developed/published in India and WHO
- Cost of the implementation of the standards
- Implication of development projects
- Primary criteria for suggesting the standard is human health.

Subsequent to the deliberations of experts and the consensus reached, CPCB has formulated the ambient air quality standards for most commonly found pollutants. Recently, the MoEF revised NAAQS and announced the notification of the new NAAQS-2009, in the official Gazette, which provides a legal framework for control of air pollution and the protection of public health. These revised Indian NAAQS-09 for criteria pollutants are summarized in Table 1 (source: MoEF, India, 2009). As per the norms, the residential and industrial areas have the same standards. These standards and guidelines address individual pollutants and their safe limits (CPCB, 2000, 2003).

Table 1. Indian national ambient air quality standards (MoEF Gazette)

Sl. No.	Pollutant	Time Weighted Average	Concentration in Ambient Air		
			Industrial, Residential, Rural and Other area	Ecologically Sensitive Area (notified by Central Govt.)	Methods of Measurements
1	Sulphur Dioxide (SO_2) µg/m^3	Annual * 24 hours**	50 80	20 80	-Improved West and Gaeke -Ultraviolet fluorescence
2	Nitrogen Dioxide (NO_2) µg/m^3	Annual * 24 hours **	40 80	30 80	-Modified Jacob & Hochheiser (Na-Arsenite) -Chemiluminescence
3	Particulate Matter (size less than 10 µm) or PM_{10} µg/m^3	Annual * 24 hours **	60 100	60 100	-Gravimetric -TOEM - Beta attenuation
4	Particulate Matter (size less than 2.5µm) or PM2.5 µg/m^3	Annual * 24 hours **	40 40	40 60	-Gravimetric -TOEM - Beta attenuation
5	Ozone(O_3) µg/m^3	8 hours** 1 hour**	100 180	100 180	-UV photometric -Chemiluminescence -Chemical method
6	Lead(Pb) µg/m^3	Annual * 24 hours **	0.50 1.00	0.50 1.00	-AAS/ICP method after sampling on EPM 2000 or equivalent filter paper -ED-XRF using Teflon filter
7	Carbon Monoxide(CO) mg/m^3	8 hours** 1 hour**	02 04	02 04	Non Dispersive Infrared Spectroscopy
8	Ammonia (NH_3) µg/m^3	Annual * 24 hours **	100 400	100 400	-Chemiluminescence -Indophenol blue method
9	Benzene (C_4H_4) µg/m^3	Annual*	05	05	-Gas chromatography based continuous analyzer -Adsorption and Desorption followed by GC analysis
10	Benzo Pyrene(BaP)-particulate phase only ng/ m^3	Annual*	01	01	-Solvent extraction followed by HPLC/GC analysis
11	Arsenic(As) ng/ m^3	Annual*	06	06	-AAS/ICP method after sampling on EPM 2000 or equivalent filter paper
12	Nickel(Ni) ng/m^3	Annual*	20	20	-AAS/ICP method after sampling on EPM 2000 or equivalent filter paper

*Annual arithmetic mean of minimum 104 measurements in a year at a particular site taken twice a week 24 hourly at uniform intervals

* 24 hourly or 08 hourly or 01 hourly monitored values as applicable shall be compiled with 98% of the time in a year. 2% of the time they may exceed the limits but not on two consecutive days of monitoring

Source : Ministry of Environment and Forests, GOI, 2009

5.5 Towards Defining Air Quality Index (AQI) for India

5.5.1 Background

Air quality standards are set by individual countries to protect the health of their citizens. As such, it is difficult to incorporate standards into a reference scale. Awareness of high air pollution concentrations and/or even the frequency of the NAAQS exceedences are not sufficient for the citizens to assess urban air quality. Information is required on the concentrations and potential health risks of air pollution which are presented in a simple, understandable format. In recent years, AQIs as suggested by the US Environmental Protection Agency (EPA) are used in many cities to highlight the severity of air pollution and risks of adverse health effects (USEPA, 2003, 2008). The AQIs are related to the overall status of air pollution via a pre-defined set of clearly identified criteria. These criteria should be universal and irrespective of the level of pollution. It should be sufficiently flexible to account for different levels of population exposure, variable meteorological and climatic conditions occurring in an area, as well as the sensitivity of flora and fauna (USEPA, 1998). The main objective of the AQI is to inform and alert the public about the risk of exposure to daily pollution levels. The computation of the AQI requires (a) measured air pollutant concentration(s). The function used to convert from air pollutant concentration to AQI varies by pollutant, and is different for different countries. Air quality index values are divided into ranges, and each range is assigned a descriptor and a colour code. Standardized public health advisories are associated with each AQI range. There are primarily two steps involved in formulating an AQI: first the formation of sub-indices for each pollutant, and second the aggregation (breakpoints) of sub-indices. The segmented linear function is used for relating the actual air pollution concentrations (of each pollutant) to a normalized number (i.e. sub-index). A linear segmented function consists of straight-line segments joining discrete coordinates (i.e. breakpoints). An index for any given pollutant is its concentration expressed as a percentage of the relevant standard (USEPA, 1998). Breakpoint concentrations depend on the NAAQS and results of epidemiological studies indicating the risk of adverse health effects of specific pollutants.

To convert from concentration to AQI following function is used:

$$I = \frac{I_{high} - I_{low}}{C_{high} - C_{low}}(C - C_{low}) + I_{low}$$

where,
I is the (Air Quality) index,
C is the pollutant concentration,
C_{low} is the concentration breakpoint that is ≤ C,
C_{high} is the concentration breakpoint that is ≥ C,
I_{low} is the index breakpoint corresponding to C_{low},
I_{high} is the index breakpoint corresponding to C_{high}.

Despite the fact that pollutant concentrations near major industries, intersections and roadways in the cities are exceeding the Indian National Ambient Air Quality Standards (NAAQS), the concept of AQI for classifying the air quality in India has only recently been paid serious attention. Earlier, a few studies have proposed AQI for some selected cities in India. Through a CPCB, MoEF, sponsored project, a study carried out at the Indian Institute of Technology (IIT) Kanpur proposed preliminary Indian Air Quality Index (IND-AQI) and breakpoint concentrations. These AQI were based on the older (2003) NAAQS of India (http://home.iitk.ac.in/). Few studies have used the AQI concept to classify pollution levels in India. Through a sponsored project from the CPCB, New Delhi, Sharma et al. (2003) have proposed the Indian Air Quality Index (IND-AQI) for the criteria pollutants SO_2 (24-h av), NO_2 (1-h av), suspended particulate matter (SPM) (24-h av), CO(24-h av and 1-h av), O_3 (24-h av and 1-h av) and PM_{10} (24-h av). In their study, a maximum operator concept was used to determine the overall AQI. The maximum value of the sub-indices of each pollutant was taken to represent an overall AQI of the location. Breakpoint concentrations depend on the NAAQS and results of epidemiological studies indicating the risk of adverse health effects of specific pollutants. In India the AQI is primarily a health related index with the following descriptor words: "Good (0-100)", "Moderate (101-200)", "Poor (201-300)", "Very poor (301-400)", "Unhealthy (401-500)", please see Table 2 as explained below in Section 5.5.2.

It is observed that breakpoints for good air quality index proposed for the criteria pollutant SO_2 (24-hour av), CO (1-hour av), NO_2 (24-hour av) and PM_{10} (24-hour av) are the same as that of the notification of the new NAAQS-2009 in the official Gazette. However, for ozone, the breakpoint proposed in the Sharma et al. (2003a) for good air quality is higher than that of the recent notification of the new NAAQS-2009 for 8-hour average ozone concentration. Linear segmented relationship for sub-index values and the corresponding concentration for $PM_{2.5}$ are not proposed in the IND-AQI (Sharma et al. 2003a), however the notification of the new NAAQS-2009 set the limit of 60 µg/m3 (24-hour av) for $PM_{2.5}$. Based on scientific judgment and available epidemiological studies, all the available recent Indian AQI studies were combined (Tiwari et al. 1987; Rao et al. 2002; Sharma et al. 2003a; Sharma et al. 2003a; CPCB, 2003; Beig and Gunthe, 2004; Badhwar et. al. 2006; Nagendra et al. 2007; Bishoi et al. 2009) with the notification of the new NAAQS-2009 (MoEF, 2009) and Air Quality Index for criteria pollutants was proposed viz, O_3, CO, NO_2, PM_{10}, and $PM_{2.5}$. Also published reports on health-related studies with respect to air pollution carried out in various urban areas by different organizations (Lahiri et al. 2000; Parivesh, 2001; Kisku et al. 2003; Kaushik et al. 2006; Jayaraman, 2007; Barman et al. 2010) were referred. In the proposed AQI the breakpoints for the criteria pollutants ozone and $PM_{2.5}$ are revised by taking into consideration the revised NAAQS, presently generated primary data set combined with epidemiological studies for India, and the US-EPA Federal Episode criteria along with the Significant Harm Level.

Table 2. The AQI sub-index and pollutant concentration breakpoints for India as proposed by Ministry of Earth Sciences

Description	Air Quality Index		Ozone (8h avg) (ppb)		CO (8h avg) (ppb)		NO_2 (24 avg) (ppb)		PM_{10} (24 avg) µ/m³		$PM_{2.5}$ (24h avg) (µ/m³)	
	I_{low}	I_{high}	C_{low}	C_{high}	C_{low}	C_{high}	C_{low}	C_{high}	C_{low}	C_{high}	C_{low}	C_{high}
Good	0	100	0	50	0	1.7	0	42	0	100	0	60
Moderate	101	200	51	98	1.8	10.3	43	94	101	150	61	90
Poor	201	201	99	118	10.4	14.7	95	295	151	350	91	210
Very Poor	301	301	119	392*	14.8	30.2	296	667	351	420	211	252
Critical/ Severe	401	500	393*	above	30.3	above	668	above	421	above	253	Above

** 8-hour O_3 values do not define higher AQI values (≥300). AQI values of 301 or higher are calculated with 1-hour O_3 concentrations*

5.5.2 Defining AQI for India in SAFAR

It was hard to provide the most realistic AQI for India without harmonizing and scientifically assessing the two most critical information bases that are (1) NAAQS and (2) the air quality with health related statistics as discussed in the previous section. The SAFAR technical report published by the Ministry of Earth Sciences (MoES) in 2010 (Beig et al. 2010) made a realistic attempt to define the AQI for India for the first time by combining the most comprehensive data base and health assessment model. The task of defining AQI by MoES under the SAFAR project has been accomplished by collecting health and air quality data on a longer time scale and adopting the health impact assessment model for 3 cities namely Delhi, Chennai and Pune. The health assessment model takes into account the long-term air quality data from the criteria pollutants, comprehensive statistics of health data for different diseases including that of hospital visits, hospital admissions, morbidity and mortality data along with weather conditions. It filters out effects likely to be occurring due to reasons other than air pollution based on set methodology. It is the first time that such model is integrated with comprehensive data repository of different pollutants on a seasonal basis.

The new NAAQS is used as baseline criteria, so that the AQI for criteria pollutants O_3, CO, NO_2, SO_2, PM_{10}, and $PM_{2.5}$ can be calculated in different ranges as practiced worldwide where an air quality forecasting system is in place and operational on a routine basis. The scientific basis for fulfilling the missing information is also briefly discussed. This concept of the AQI is especially of important in India, where the common man is not very familiar with technical terminology and measuring units (such as ppm /ppb /ppt or µg/mg3). Hence the AQI (which is represented in unitless numbers) and its categorization in different colours, which are based on the quality of air with respect to human health, will pave the way for the public to understand its impact in most simplistic manner. It is also felt that at this juncture when the country is heading towards the development under MoES and WMO of the first air quality forecasting system for different cities, it is an appropriate time to define the AQI for India. This scientific basis will pave the way to adopt or release the AQI by implementing agencies in India for the benefit to society.

The AQI sub-index and breakpoint pollutants concentrations for India with the respective colour coding as proposed by MoES are shown in Table 2. As evident from this table, there are a few breakpoints which are found to be agreeing to the earlier studies which complement the importance of the work carried out by earlier workers. The key reference point in the calculated AQI value is 100 indicating a safe limit based on the latest attainment of NAAQS for India (MoEF, 2009).

To reflect the attainment of NAAQS for ozone, instead of 157 µg/m3 (~79 ppb), we propose 100 µg/m3 (50 ppb) breakpoint for the 'Good' AQI (0-100). In absence of any ozone health criteria in India, the rest of the Index categorization is scaled to the breakpoints criteria proposed by *Sharma et al.* (2003, 2003a). For the second breakpoint (at the standard of USEPA) we propose 196 µg/m3 (98 ppb) breakpoints for the 'Moderate' AQI (101-200), 235 µg/m3 (118 ppb) breakpoints for the 'Poor' AQI (201-300). 8-hour O_3 values do not define higher AQI values (≥300). AQI values of 301 or higher are calculated with 1-hour O_3 concentrations. Scientifically it is important to understand that high ozone concentration of 240µg/m^3 and above corresponding AQI beyond 300 has strong health implications such as scarring of lung tissues. Short-term exposure to such high concentrations of ozone can cause substantial damage to the respiratory system. These damages may advance even after the symptoms have subsided. (WHO, 2005)

Keeping this criterion in mind, 8-hour is superseded with 1-hour average if AQI crosses the 300 limit. Similarly, to reflect the attainment of NAAQS for $PM_{2.5}$, we proposed 60µg/m3 breakpoint for the 'Good' AQI (0-100). WHO, in their approach, convert $PM_{2.5}$ guideline values to the corresponding PM_{10} guideline values by application of a $PM_{2.5}/PM_{10}$ ratio of 0.5. A $PM_{2.5}/PM_{10}$ ratio of 0.5 is typical of a developing country's urban areas and is at the bottom of the range found in the developed countries urban areas (0.5-0.8) (WHO, 2005). WHO further notes that when setting local standards, if relevant data are available, a different value for this ratio; i.e. one that better reflects local conditions, may be employed. Based on available measurement of $PM_{2.5}$ and PM_{10} from different places (Shukla, et al. 2006; Barman et al. 2008; Badhwar et al. 2006), we have observed that the percentage difference between annually averaged PM_{10} and $PM_{2.5}$ concentration is approximately 40% - 50% for most of the cities in India. Also, the percentage difference between PM_{10} and $PM_{2.5}$ in the new NAAQS-2009 is 40%.

Based on the health criteria determined using the data base referred to above, it is concluded that rest of the categorization of AQI for $PM_{2.5}$ should be scaled to 40% lower than the PM_{10} index for all categories. Although it is found that the $PM_{2.5}$ to PM_{10} ratio for Delhi is slightly higher than that of many other cities of India, we have adopted the above percentage classification. This is done to generalize and keeping the fact in mind that we are working to provide the AQI for a country as a whole and it is the best approximation at the present time. For the second $PM_{2.5}$ breakpoint we propose 90 µg/m3 breakpoint for the 'Moderate' AQI (101-200), 210 µg/m3 breakpoint for the 'Poor' AQI (201-300), 252 µg/m3 breakpoint for the 'Very Poor' AQI (201-300), and above 252 µg/m3 for critical. In Figure 5 the links between AQI values and health advisories is shown.

Good (0-100)	No cautionary action required	Air pollution poses little or no risk.
Moderate (101-200)	Unusually sensitive people should consider reducing prolonged or heavy exertion and heavy outdoor work.	AQ acceptable for general public but moderate health concern for sensitive people
Poor (201-300)	People with heart or lung disease, older adults, and children should reduce prolonged or heavy exertion.	Increasing likelihood of respiratory symptoms in sensitive individuals. Children and elderly at risk. Everyone may begin to experience some level of discomfort.
Very Poor/ Unhealthy (301-400)	People with heart or lung disease, older adults, and children should avoid prolonged or heavy exertion; everyone else should reduce prolonged or heavy exertion.	Triggers Health alert. Eveyone may experience more or serious health effects. Significant increase in respiratory effects in general population.
Severe /Critical (401-Above)	Everyone should avoid all physical activity outdoors; people with heart or lung disease, older adults, and children should remain indoors and keep activity levels low.	Health Warning of Emergency Conditions. Serious risk of respiratory effects in general public.

Figure 5. Different categories of AQI shown in different colours and associated health impacts

(1) **Good: AQI (0-100):** Health effect: Air quality is good / acceptable, there is very little or no risk for general public. Precautionary measures are not required.

(2) **Moderate: AQI (101-200):** Health effect: Air quality is acceptable for general public. It will be better if sensitive people like patients suffering from respiratory and heart diseases avoid prolonged outdoor activities.

(3) **Poor: AQI (201-300):** Health effect: General public may experience some discomfort/health effects during regular activities. It is unhealthy for a group of sensitive people; children and older people may get affected by outdoor activities by environmental exposure.

(4) **Very Poor: AQI (301-400):** Health effect: Unhealthy for general public, everyone will experience more or less health effects. There is a need to take precautionary measures.

(5) **Critical/ Severe: AQI (401-500):** It is an emergency alarm for everyone. Immediate precautionary measures are required.

6. DEVELOPMENT OF HIGH-RESOLUTION EMISSION INVENTORY

Most megacities all over the world are experiencing the deterioration of air quality, including the National Capital Territory (NCT) of Delhi. The pollutants are added to the environment through emissions of various natural as well as anthropogenic, i.e. man-made, sources. The anthropogenic emissions are on the rise due to human intervention and mainly responsible for deteriorating air quality in recent times. An emission inventory is a comprehensive listing of air pollutant emissions by sources and amounts of air pollutants released into air, as a result of a specific processes in a particular geographic region during a specific time period. This is one of the most critical factors required for 3-D atmospheric chemistry transport models along with meteorological input to forecasting the air quality that can be used for instance for mitigation. The quality of forecasting depends on the accuracy and reliability of emission estimations. Emission inventories can also be used for air quality management and formulating environmental policy.

Development of an emission inventory in a megacity in a developing country is a complex process due to numerous, diverse and widely dispersed emission sources. In a city like Delhi, and its adjacent regions this requires a huge amount of high-resolution activity data, emission factors along with knowledge of fundamental scientific processes. Scientists of MoES are involved in this area of research, for more than a decade, at IITM, Pune, and have published a first ever inventory of several pollutants for our country India in international journals (Sahu et al., 2008; Beig and Brasseur, 2006). Since then, MoES has taken up the mission mode project called SAFAR to forecast the air quality of NCT Delhi for the first time in our country on the occasion of the Commonwealth Games-2010. A comprehensive study based on scientific knowledge has been made to develop the high-resolution (1.67 km x 1.67 km) emission inventory of all major air pollutants for a domain of ~65 km×70 km (~4500 km^2 area) covering Delhi and its adjacent region to facilitate accurate air quality forecasting. Emission inventories have been developed for eight air pollutants namely, NO_X, CO, BC, Organic Carbon (OC), $PM_{2.5}$, PM_{10}, SO_2, and VOCs.

For the development of the emission inventory, a bottom up approach has been used for which a Geographical Information System (GIS) based statistical model was developed by our scientists at IITM to prepare a high-resolution gridded emission inventory. The emissions have been estimated for the individual sources and for that purpose, an extensive scientific field campaign was carried out in the NCT region during several months by involving more than 250 students from different colleges and universities in Delhi and Pune, by which the feeling of scientific temperaments in young minds was also achieved. The main focus of the campaign was to generate missing primary data, validate some uncertain secondary data and to collect the available secondary data. During the campaign, information related to following major activities was collected from relevant institutions regarding the quantity of fuel used, their type and daily usage:

(1) Power (coal used in all thermal power plants)
(2) Transport sector (compressed natural gas (CNG), diesel, petrol driven vehicles, etc.)
(3) Industrial (fuel used in cement, steel, bakery, chemical, metal industries, etc.)
(4) Slum cooking (use and type of kerosene, wood, coal etc.)
(5) Commercial cooking (in hotels, restaurants)
(6) Street vendor fuel usage survey
(7) Paved /unpaved road (dust release)
(8) Industrial /shop generator sets (diesel used)
(9) Bio-fuel burning (dung, crop-residue, wood, biomass, etc.)
(10) Open trash burning

To know the traffic volume on different major and minor roads and at traffic junctions in NCT region, vehicle number densities were counted using click counters at various traffic junctions and busy locations in the NCT region by students. Delhi has a major road network of nearly 2150 km as compared to minor road network of around 30000 km and it was found that 67% of vehicular density runs on major roads. Delhi not only has vehicles from within the city but huge numbers of vehicles enter from outside Delhi region as well. Major traffic junctions contributing to high emission are identified. Most of the secondary data updates are collected from different governmental resources and primary data are generated by team of IITM scientists with the help of volunteers and research students.

The above sources of emissions are further categorized in 5 major sectors namely:

(1) Transport (fossil fuel-petrol, diesel, CNG)
(2) Bio-fuel (res. and comm. cooking-wood, coal, kerosene, open biomass;
(3) Power (coal burning in thermal power plants)
(4) Industry (all other industries)
(5) Suspended dust /others (paved and unpaved road, construction activities, brick Kiln, wind-blown)

Industrial and power sector includes emissions from fossil fuel burning, residential sector involves major sources such as fuel (bio-fuel, fossil fuel) burning in slums, hotels, street vendors etc. while transport sector involves emissions from different types of vehicles according to their age, fuel used and present engine technology

6.1 Generation of activity data and emission factors

6.1.1 Activity data

Activity data is defined as the quantitative measure of the activity that results in the emissions of air pollutants. Different kinds of activities are related with a particular source of emission and so there is a need to consider all these activities for exact quantification of the emissions. It was not feasible to monitor all the sources (like industries, thermal power plants etc), hence most of the primary data has been generated for four sources including on road vehicles, slums, street vendors and hotels and restaurants, while secondary data was collected for industrial stacks and thermal power plants.

a) Primary data collection

Primary data was obtained from collecting representative samples from the area of interest (AOI). The purpose of generating primary data was to obtain the unavailable data. The emission inventory of Delhi-NCT for CWG-2010 was developed to confirm the authenticity of the previously available data and to improve the accuracy and reliability of the inventory by updating them. To collect such samples and to know the present scenario in the AOI, an extensive field survey was carried out during a several months long campaign in the beginning of the year 2010. Around 250 college students from different colleges and universities in Delhi, as well as from Pune, were involved in the field survey and campaign. In addition to this, the in-house data repository and experiences gained during the past several years as part of the ongoing emission inventory research of IITM, have been utilized. During the survey, street vendors and officials of hotels and restaurants were interviewed to know the exact prevailing situation. Discussion was carried out for understanding the usage pattern of fuel for cooking in slum areas, by street vendors, hotels and restaurants. On an average about 10-15 households among 40 slum pockets were surveyed. The survey also included 370 different street vendors at random all across the AOI and about 690 hotels within the AOI. To know the traffic volume on different major and minor roads and traffic junctions in the AOI, the vehicle number densities have been counted using click counters at various traffic junctions and busy locations, for 20 days. The vehicle count on the roads varied according to the time of the day, hence counting was done at various hours during the day. The counting network was developed by randomly selecting 48 junctions all around the AOI. These junctions were selected after a reconnaissance survey and discussions with local people, students and authorities considering various inlets to the NCT, and also designed to include the multimodal and multifunctional characteristics of the vehicular population in the city.

b) Secondary data collection

Information or data available regarding number of slums, hotels, location of different industries, thermal power plants, number of registered vehicles, etc., were also collected from the secondary sources. The data related to the fuel consumption in industries and thermal power plants has been obtained from the published official governmental resources. Secondary data for each of the sources mentioned above was gathered from the respective agencies.

6.1.2 SAFAR emission inventory and field campaign

Under the project SAFAR a high-resolution (1km x 1km) emission inventory has been developed by the Earth System Science Organization at IITM (ESSO-IITM) for NCR-Delhi and for PMR-Pune by using a bottom-up approach. Development of an emission inventory is a complex process and requires a very large amount of activity data and knowledge of fundamental scientific processes. The accuracy and reliability of the emission inventory has been obtained by collecting unique region specific activity data during the extensive field survey that took several months and involved more than 250 students of various educational organizations, please see photos below. The main focus of the campaign was to generate missing primary data, validate some uncertain secondary data and to collect the available secondary data. Proper country specific emission factors have been selected to estimate the total emissions of nitrogen oxides (NO_X); carbon monoxide (CO); black carbon (BC); organic carbon (OC); $PM_{2.5}$ and PM_{10}; sulphur dioxide (SO_2) and VOCs from transport, industrial, residential, and slum sectors. The particulate emissions from untouched sources, paved and unpaved roads, are also estimated. The spatial distribution of pollutants has been studied by using a GIS based statistical model.

Slum

Residential

Transport

Street vendor

6.1.3 Emission factors

An emission factor (EF) is a representative value that attempts to relate the quantity of a pollutant released to the atmosphere with a particular activity associated with the release of that pollutant. Typically, EFs of a fuel depend on the chemical composition of the fuel, combustion type, temperature, and efficiency of any emission control device. There are very limited measured EFs available in literature for India. Incorporating a country specific appropriate EF is a very sensitive part in the development of an emission inventory. EF defines the source strength as emission per unit time and per unit activity of the process. Country specific technology based EFs for most of the sectors are not yet available for India. Hence, in the development of the emission inventory, selection of an appropriate EF for a fuel type for a specific country is extremely meticulous work. Even a minor change in the EFs has the potential to alter the total emission inventory. The EFs used in the present work were collected with valid scientific judgments and relying on acceptability by the global community. The scientific justification for the chosen EFs was also discussed. The EFs used for the development of the emission inventories of different pollutants were discussed in respective sectors along with the activity, these have been described above.

6.2 Some results on emissions of pollutants

The brief summary of estimated emissions for 2009-2010 is given in Tables 3 and 4. The detailed methodology, its scientific basis and interpretation of the newly developed emission inventory are available in the technical report released by our ministry as an IITM Research report. However, some of the pollutants are briefly discussed here, so as to demonstrate the quantity of detailed work carried out during the study.

It was observed that transport and industrial sectors are the two dominant sectors responsible for the majority of gaseous pollutant emissions in Delhi, followed by residential and power sectors. As far as particulate pollutants are concerned, the major contributors are the transport sector and suspended dust followed by bio-fuel and industry. The unpaved road dust has a high potential of enhancing the emissions of particulate matter. The transport related emissions were greatly curbed due to the introduction of CNG in Delhi during 2003 but the gain seems to have been lost by now due to the increase in the number of vehicles since then. NO_X emissions are on the rise whereas BC emissions are quite low.

Hence, while formulating and implementing the mitigation strategies, above should be kept in mind. The study reveals several interesting features and hot spots which may not deteriorate the air quality for that particular spot due to dynamical meteorology but will impact other regions through the transport of pollutants. The development of the emission inventory is still in an evolving stage, and some amount of uncertainty in the results was observed, however, it is considered that within the constraints, the emission estimates provided for NCT region Delhi are highly robust on such a finer resolution. The results will go a long way in helping the air quality management system, environmental policy makers and improving the accuracy of air quality forecasting.

The emission inventory developed for AOI in Delhi NCT (70 km x 65 km) reveals that the total estimated CO, NO_X, SO_2, VOCs, and OC emissions are around 703 Gg/yr, 255 Gg/yr, 322 Gg/yr, 465 Gg/yr, and 18.4 Gg/yr respectively, see Table 3.

Table 3. Emissions (in Gg/yr) of various air pollutants by different sectors for the year 2010 in the area of approx. 70 km x 65 km covering major parts of National Capital Region of Delhi

Air pollutants Emissions from different sectors (2010)					
SECTOR	**CO**	**NOx**	**SO_2**	**VOCs**	**OC**
Power	0.29	6.9	57.6	0.1	0.004
Industry	10.9	79.8	210	34.8	12.6
Transport	428	162	47.3	419	3.2
Residential	264	6.4	7.23	10.7	2.6
TOTAL	703	255	322	465	18.4

The spatial distribution of emissions from all sources over Delhi and its adjacent NCT region for the year 2009-2010 is discussed briefly. The estimated total emission of $PM_{2.5}$ for Delhi is calculated to be around 68.1 Gg/yr in 2010 without suspended dust emissions. High emissions of the order of 50-400 ton/yr were found over Rajiv Chowk, Sansadn Bhawan, India Gate, Indira Gandhi international airport, Okhala Industrial Area, Pragati Maidan, IP-estate, Janakpuri, Meharoli, Lakshminagar amongst others. Large point sources such as thermal power stations and major industrial zones, are the major contributors of $PM_{2.5}$ with an order of 500-9000 ton/yr. $PM_{2.5}$ emissions for street vendors followed by slum cooking contributes the maximum to the total emissions from the residential sector where coal, kerosene and liquid petroleum gas (LPG) is used at very low combustion and scattered widely over the dense population. Emissions from transport and industrial sectors are almost similar. There has been a reduction in $PM_{2.5}$ from the transport sector after the implementation of emission norms in Delhi in 2000-2003 by bringing in CNG, improvement in fuel quality and defining the Indian Bharat stage-2, 3 emission standards, etc. The spatial distribution of $PM_{2.5}$ emissions from all sources is given in Figure 6a. The estimated emission of $PM_{2.5}$ is calculated as around 68.1 Gg/yr in 2010 from various sectors excluding the windblown suspended dust. The relative contributions from different sectors are shown in Figure 6b including suspended dust. The windblown dust contributes to 26.2 Gg/yr (28%) of $PM_{2.5}$ emissions in Delhi as shown in Table 4. Hence, it becomes the 2nd largest sector after transport.

Table 4. Estimated emissions (in Gg/yr) of particulate pollutants by different sectors for the year 2010 in the area of approx. 70 km x 65 km covering the National Capital Territory (NCT) Delhi. The total is expressed with (Aggregate) and without (w/o) the suspended dust.

Particulate Emissions - Delhi-NCT-2010 Gg /year			
SECTOR	PM10	PM2.5	BC
Power	11.02	2.87	0.04
Industry	27.2	16.3	8.67
Transport	35.5	30.3	9.77
Bio-fuel	36.1	18.7	2.96
Total (w/o suspended dust)	110	68.1	21.4
Other (Suspended Dust)	126	26.2	NIL
AGGREGATE TOTAL	236	94.2	21.4

(a)

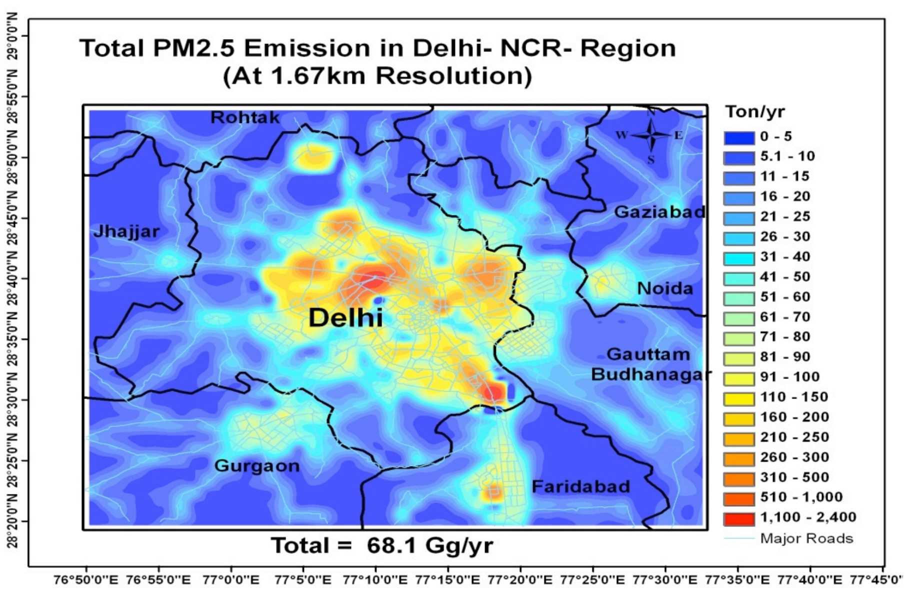


Figure 6a. Geographical distribution of $PM_{2.5}$ emissions from all sources in Delhi-NCT

(b)

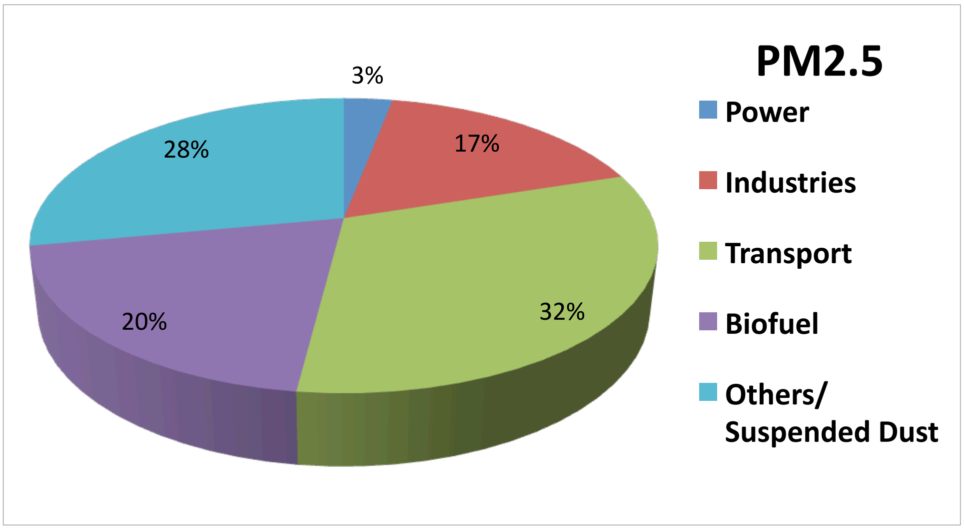


Figure 6b. Relative contributions of $PM_{2.5}$ emission from different sectors including suspended dust

The transport sector is the dominating source for CO emissions in the above discussed regions due to high population density resulting into high vehicular density and a major road network. The second most dominant source is major slum clusters, which are confined to the Central, Eastern, and south-eastern part of Delhi. Also a few surrounding regions with highly dense road networks are observed as an equally dominant source. It is seen from sector specific CO emissions that the above mentioned regions are receiving significant amounts of emissions from the transport sector, slum cooking, street vendors and commercial cooking. The distribution of CO emissions over the Delhi region is shown in Figure 7.

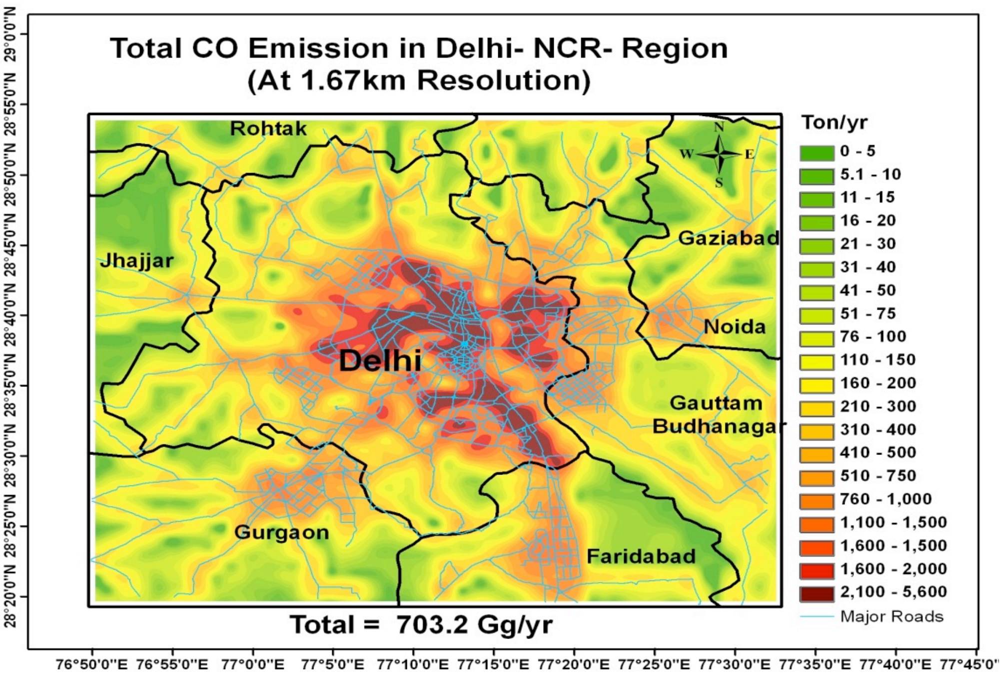
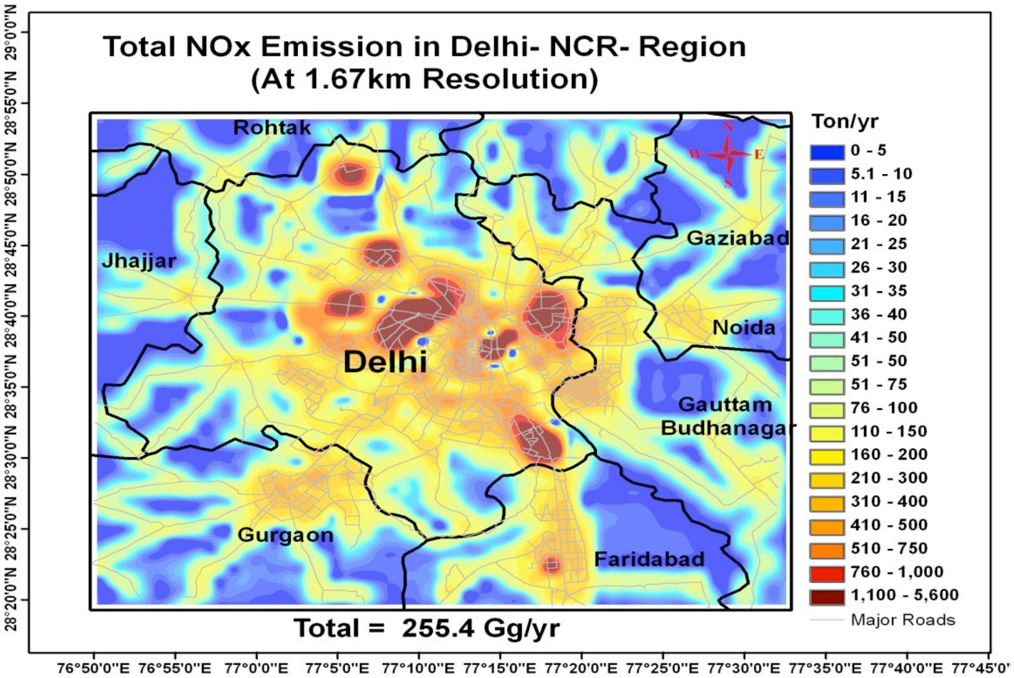


Figure 7. Geographical distribution of CO emissions from all sources in Delhi-NCT

The estimated NO_X emissions are found to be around 255 Gg/yr. The geographical distribution of total NO_X emissions and relative contributions from main sectors to the total emission estimation in the form of a pie chart are given separately in Figures 8a and 8b. The relative contributions of NO_X from the power, industrial, transport and residential sector are found to be around 2.7%, 31.2%, 63.5% and 2.5% respectively.

(a)



(b)

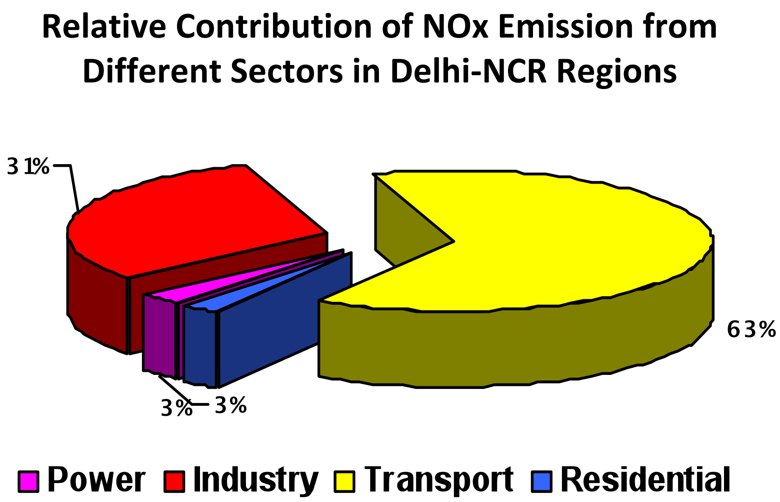
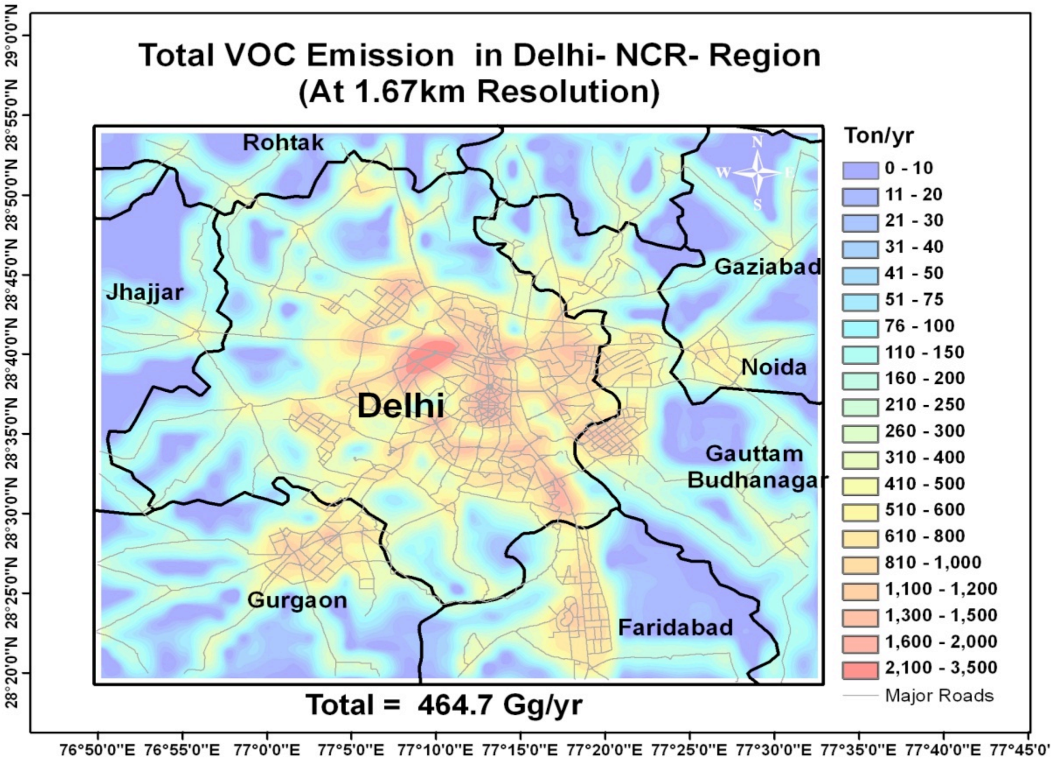


Figure 8a. Geographical distribution of NOx emissions from all sources in Delhi-NCT and Figure 8b relative contributions of different sectors for NOx emissions

The spatial distribution of total VOC emissions from all sources and relative contributions from different sectors to total VOC emissions is depicted in the form of a pie chart in Figure 9b. The VOC emissions from all sources is estimated to be around 465 Gg/yr where the transport sector plays the major role. In Figure 9a, high VOC emissions of the order of 600-3500 ton/yr are found over major road networks and junction in central and eastern Delhi regions. The relative contributions of VOCs from power, industrial, transport and residential sector are found to be around 0%, 7.5%, 90% and 2.5% respectively.

(a)



(b)

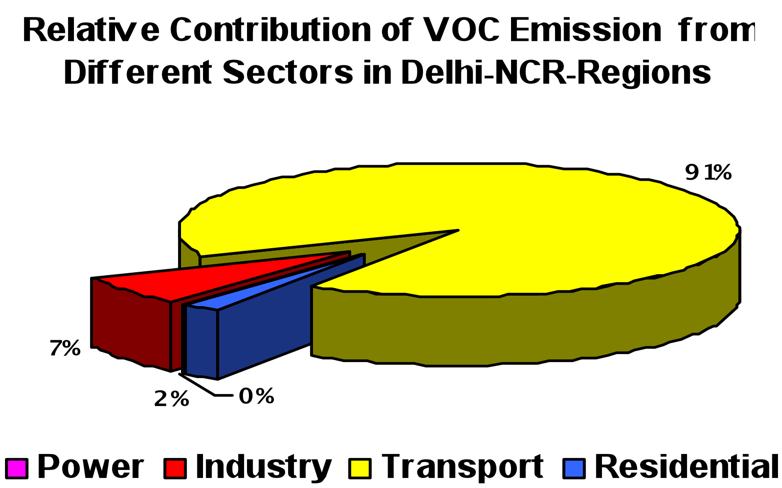
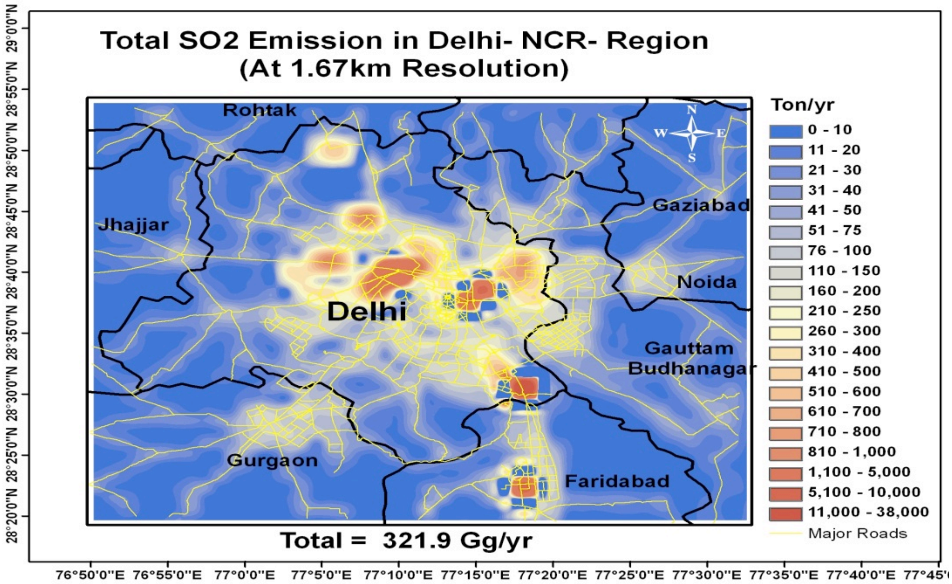


Figure 9a. Geographical distribution of VOC emissions from all sources in Delhi-NCT and Figure 9b relative contributions for VOC emissions from different sectors

The estimated geographical distribution of total SO_2 emissions and relative contributions from different sectors are shown in Figure 10a and Figure 10b respectively. The estimated total SO_2 emission is calculated to be around 322 Gg/yr. Coal used in different industrial processes and consumption of other fuels plays an important role in SO_2 emissions. The relative contribution of SO_2 from the industrial sector is around 65% (210 Gg/yr) followed by power (18%) and transport (14.7%) sectors, as shown in Figure 10b.

(a)



(b)

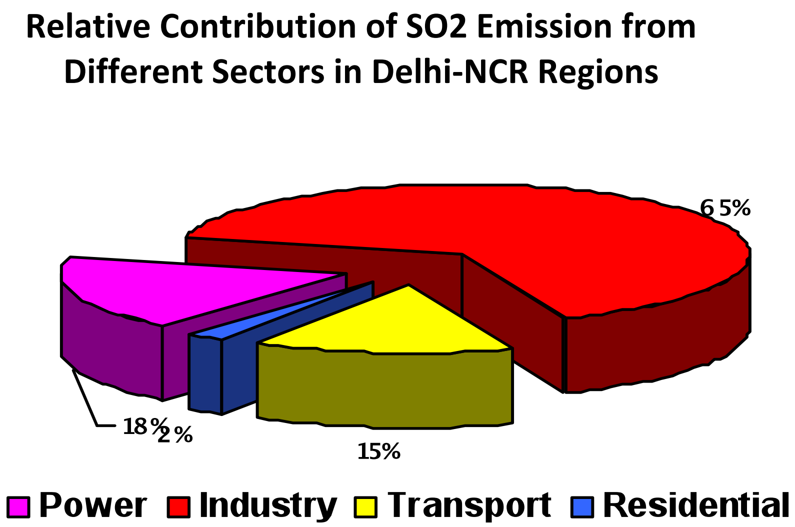
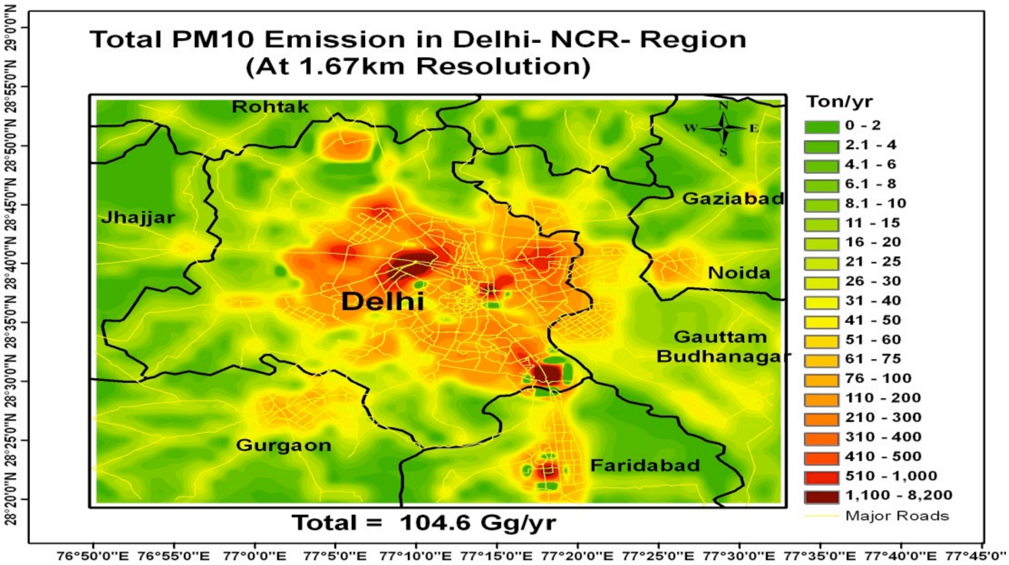


Figure 10a. Geographical distribution of SO_2 emissions from all sources in Delhi-NCT and Figure 10b relative contributions of SO_2 emissions from different sectors

Figure 11a depicts the spatial pattern of total PM_{10} emission from all sources which is estimated to be around 105 Gg/yr without suspended dust. Suspended dust plays a major role in total PM_{10} emissions. The relative contributions of different sectors to total PM_{10} emissions along with suspended dust is shown in Figure 11b where power, industrial, transport, residential (biofuel) and others (suspended dust) sectors contribute 5% (11Gg/yr), 12% (27.2Gg/yr), 15% (30.3Gg/yr) 15% (36.1Gg/yr) and 53% (126Gg/yr) respectively. As shown in Table 4, the role of suspended dust in Delhi is significant and dust contributes much more than the total emissions from other sources. The contribution of suspended dust in PM_{10} emissions is 126Gg/year.

(a)



(b)

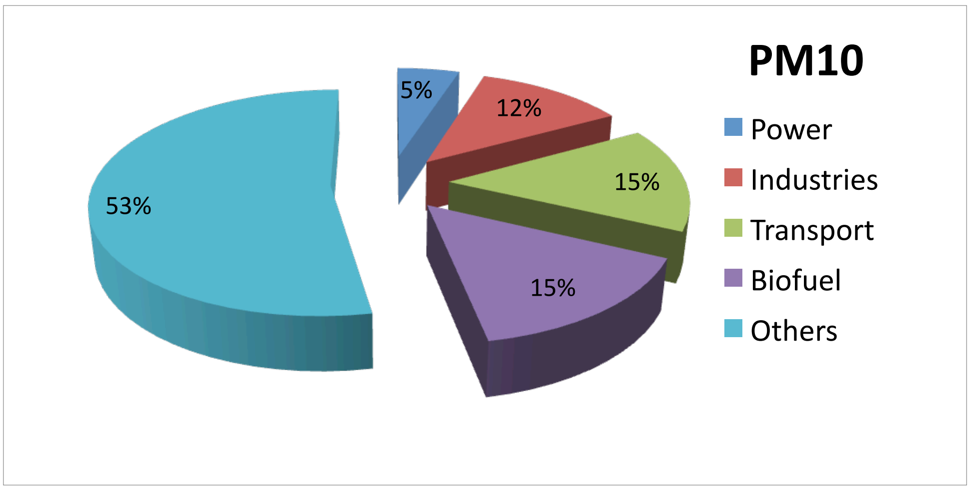
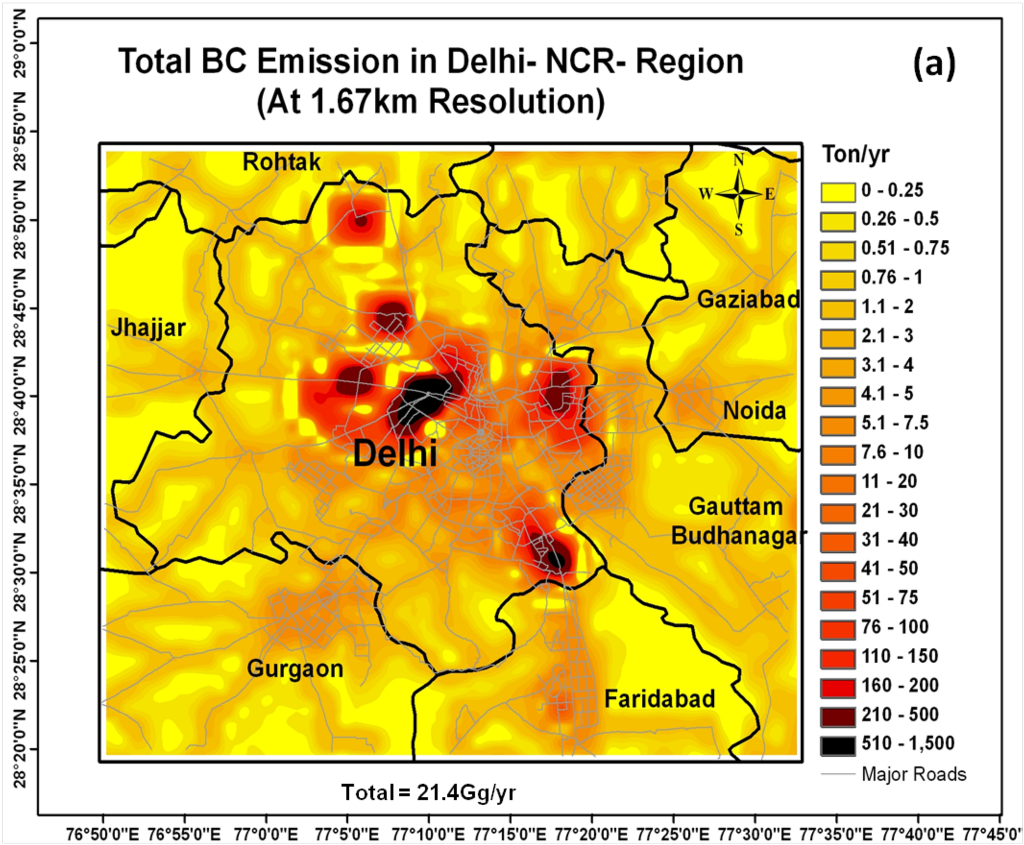


Figure 11a. Geographical distribution ofPM$_{10}$ emissions from all sources in Delhi-NCT and Figure 11b relative contributions of PM$_{10}$ emissions from different sectors (including dust emissions)

The geographical distribution of total BC emissions is shown in Figure 12a where the calculated value is around 21.4 Gg/yr and the relative contributions from each sector are depicted in Figure 12b. The contributions of BC from power, industrial, transport and residential sectors are found to be around 0.04Gg/yr, 8.67Gg/yr, 9.77Gg/yr and 2.96Gg/yr respectively, transport and industry sectors are the most dominant.

(a)



(b)

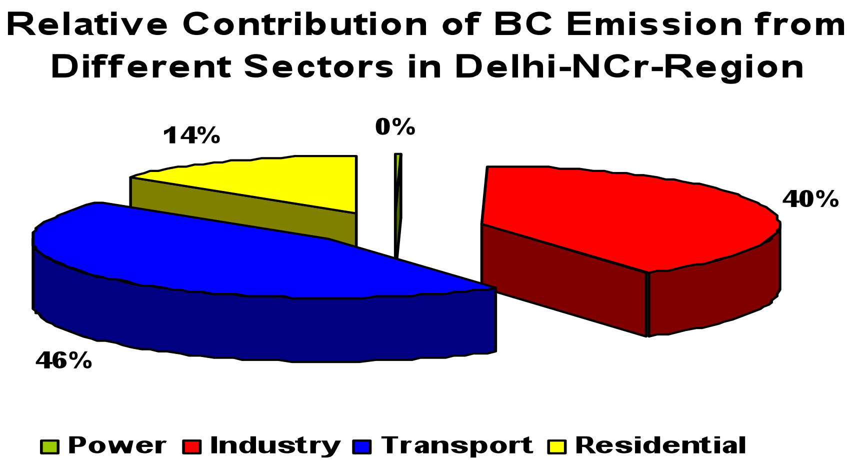
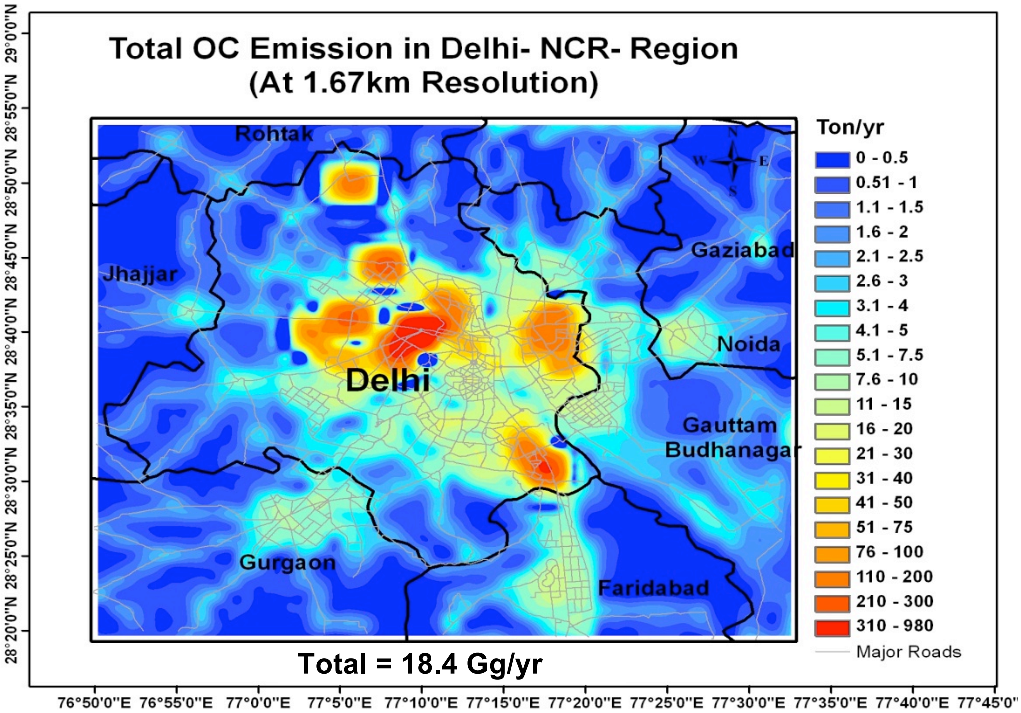


Figure 12a. Geographical distribution of BC emissions from all sources in Delhi-NCT and Figure 12b relative contributions of BC emissions from different sources

The spatial distribution of total estimated OC emissions from all major sectors is given in Figure 13a this is found to be around 18.4 Gg/yr. The contributions of OC from power, industrial, transport and residential sectors are calculated to be 0.004 Gg/yr, 12.6 Gg/yr, 3.2 Gg/yr and 2.6 Gg/yr respectively as shown in Figure 13b. Identified OC emission hotspots are found to be of the order of 100-900 ton/yr over the industrial zones.

(a)



(b)

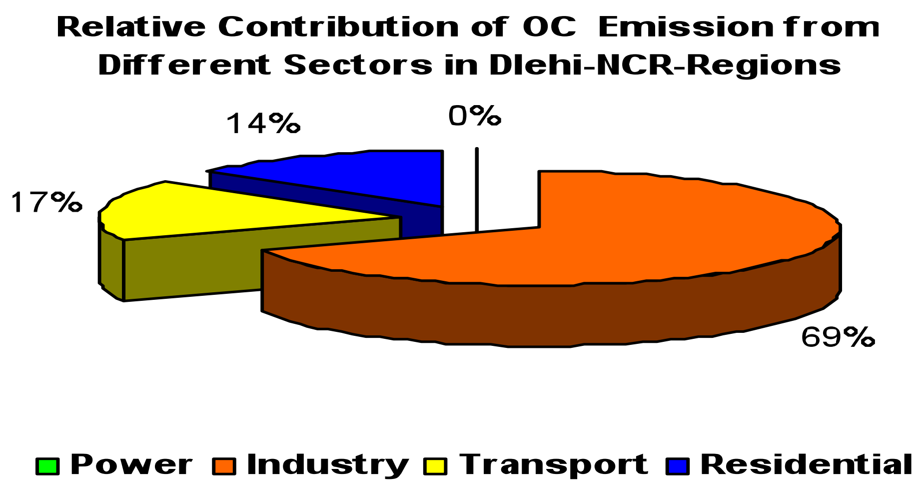


Figure 13a. Geographical distribution of OC emissions from all sources in Delhi-NCT and Figure 13b relative contributions of OC emissions from different sectors

7. MICRO-SCALE MONITORING NETWORK

7.1 Strategic monitoring locations

In SAFAR Delhi an integrated Air Quality Monitoring System (AQMS) was set up along with Automatic Weather Stations (AWS) at 10 different strategic locations within the NCR including Delhi and surrounding area of 60 x 70 km. Measurements of CO, NO_X, HCs (benzene, toluene and xylene), Hg, PM_{10}, $PM_{2.5}$, BC and OC, is being made at about 3m above ground, with the AQMS stations consisting of online pollutant analyzers. Since the project was launched during the CWG-2010 event, it was necessary to provide air quality information for the venue of the event and its nearby premises precisely, along with for other parts of the city. Later on, these monitoring stations were relocated. The 10 locations were purposefully selected so as to represent all kinds of localities in NCT. Pollutants from all the pollution sectors are necessary to be measured. Measurement and monitoring from urban, rural, residential, industrial, etc., localities was important in order to cover all types of pollution sources. The list of the 10 the AQMS stations in NCT with the map is given in Figure 14.

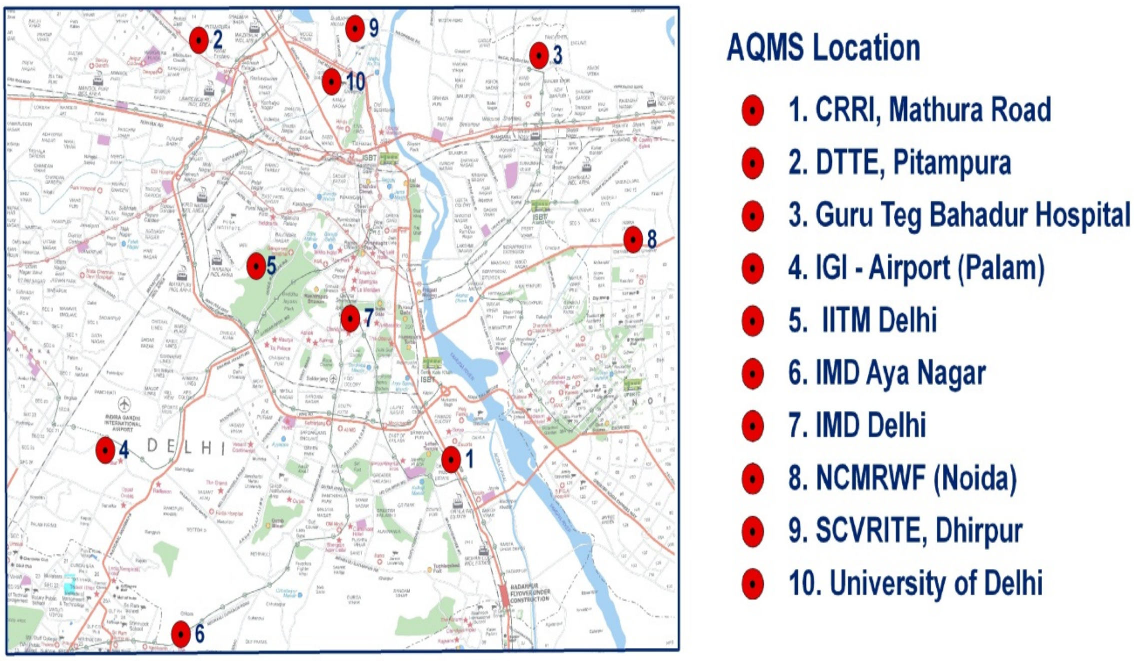


Figure 14a. Monitoring stations in NCT

Monitoring Stations

Sr.No	AQMS Locations	Latitude (Degree decimal)	Longitude (Degree decimal)
1.	IITM, Delhi	28.64	77.17
2.	Delhi University	28.69	77.21
3.	IGI Airport	28.56	77.09
4.	NCMRWF, NOIDA	28.63	77.36
5.	CRRI, Mathura road	28.55	77.28
6.	IMD Aya Nagar	28.48	77.13
7.	IMD Lodhi Road	28.59	77.24
8.	DTTE, Pitampura	28.70	77.16
9.	CVR, Dheerpur	28.73	77.20
10.	NISE, Gurgaon	28.42	77.14

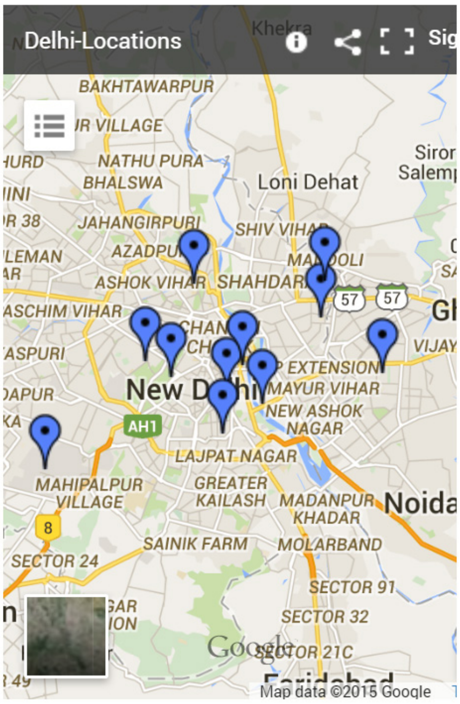


Figure 14b. Relocated stations after CWG-2010 for better coverage of Delhi NCT and for regular operational forecasting

Figure 14c. A monitoring station located in NCT

7.2 Quality assurance and quality control

Quality control and quality assurance is the major and essential step performed by the scientist of IITM before releasing the air quality data to the public in the form of the Air Quality Index (AQI). The quality of data recorded at different monitoring stations is checked 24x7 before giving as model input. Data from all the monitoring stations is received at the FTP server, in the SAFAR control room. Depending on the performance of the sensor different quality codes are assigned to physically measured air pollutant values. Data with specific codes is only accepted, which is directly representative of the good working conditions of the sensor. Data is received continuously from different sensors, monitored by a graph so that any gap/break in the data can be marked immediately and corrective measures can be taken. Failure in functioning of any of the stations or any sensor at the station can be immediately observed on the map which is showing real time working conditions of the stations and sensors. Different colour codes are assigned to working conditions of the sensors so that any change in performance can be identified immediately. Sample screenshots are given in Figure 15a.

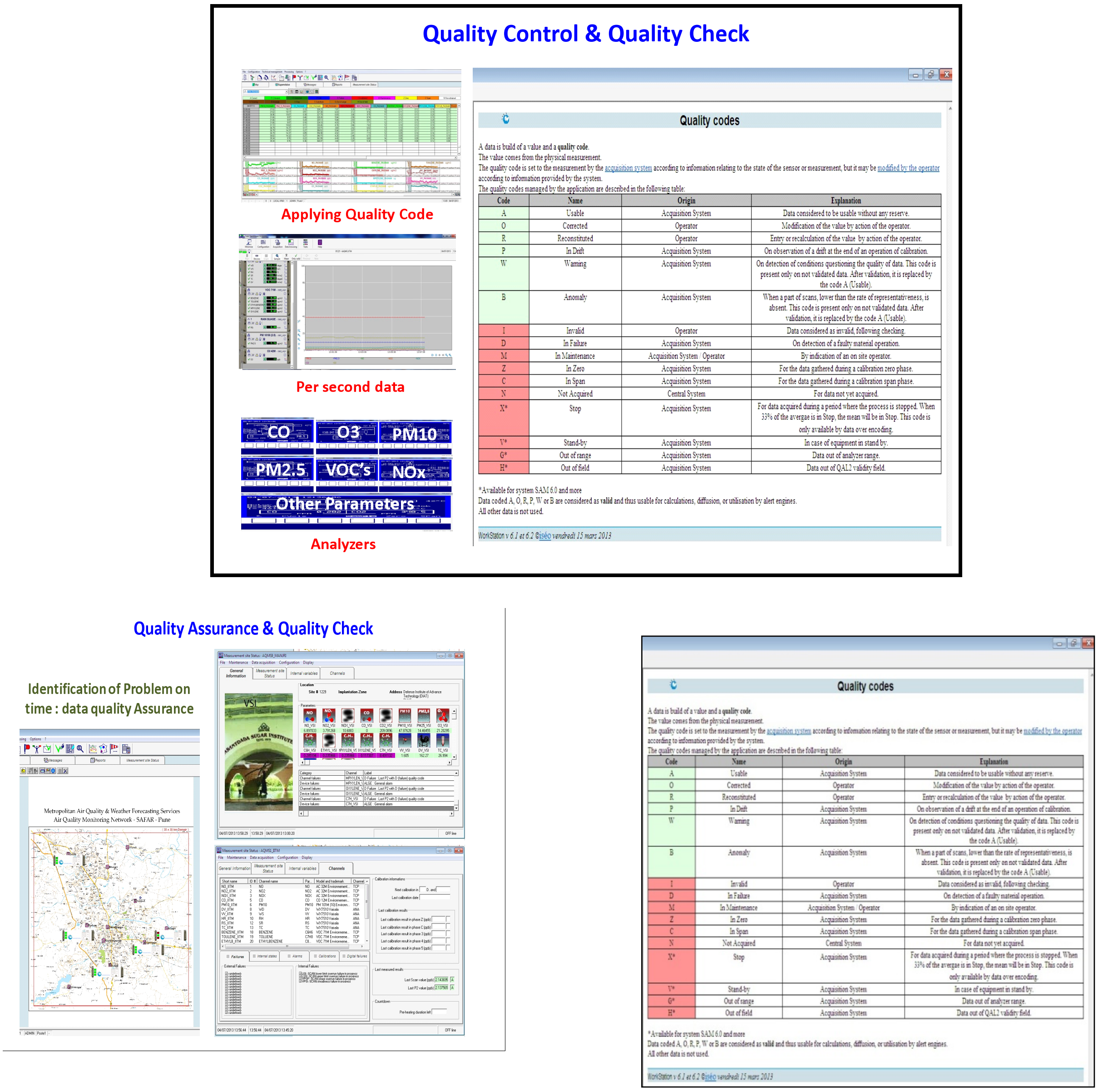


Figure 15a. Quality assurance and quality check of the data-screen shots

Before the data are transferred from the FTP server to display servers they are strictly checked for quality. Thus, if there is any malfunctioning during the data processing, it can then be identified and corrected. With this the data are quality assured and controlled, so that the dissemination to the common public is as accurate as possible.

INSTRUMENT CALIBRATION: The equipments are maintained and operated according to the standard specifications of supplier. The instruments are US EPA approved and the quality system is certified ISO-9001; 2008 by Bureau Veritas Certification. We have adopted US EPA's Standard Operating Procedures for instrument calibration and maintenance. For more information about calibration procedure refer to title 40 of the Code of Federal Regulations (CFR) part 50. http://www.law.cornell.edu/cfr/text/40/part-50.

REVIEW AND AUDIT: Our field engineers visit the stations daily and perform checks to ensure the proper working of the instruments. On the basis of drift specification, instrument environment and other factors the calibration is done at definite time intervals. Field engineers are responsible for reporting the daily status of instrument health to IITM's data validation staff which information is then fed into the SAFAR data quality assurance programme.

On a monthly basis a review meeting is conducted and monthly audits are performed in which instrument health as well as documentation is checked by internal auditors. If a monitoring station fails an audit, the audit team performs daily audits until the station passes.

ONLINE MONITORING: We are monitoring air quality indicators and weather parameters round the clock. At SAFAR control room the robust quality check system is in place which provides alert for three major conditions (1) Instrument failure at site (2) Communication failure between instrument and local server (3) Communication failure between local server & central AQMS server. This state of the art technology prevents data loss and helps to solve the problem if occurred at any specific location, with minimum time lag. The remote visualization of each station at the master control room of SAFAR is shown in Figure 15b and the online monitoring of various pollutants in Figure 15c.

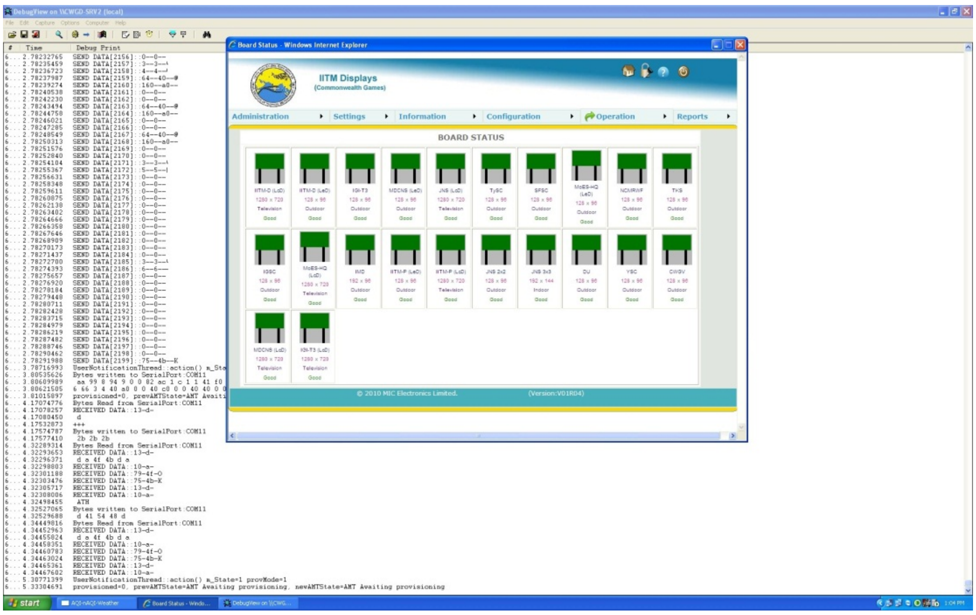


Figure 15b. Quality assurance and quality check of the data: visual remote

DATA VALIDATION: Validation is an essential function of technical management. At the SAFAR control room errors or suspicious data has been flagged by the system which is then checked and corrected by an expert scientific team. Various quality codes are set to observational values based on information relating to the state of the sensor or measurement.

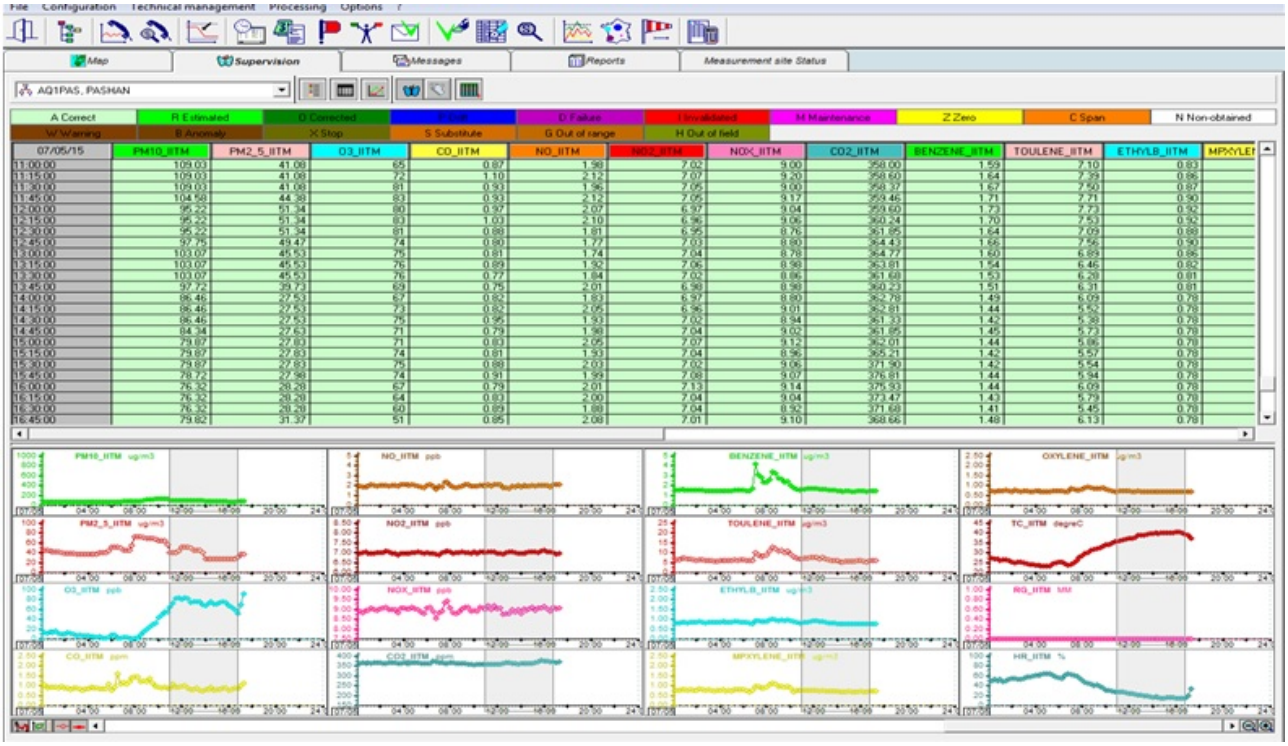


Figure 15c. Quality assurance and Data check online monitoring of various air pollutants

7.3 SAFAR Control Centre

The SAFAR Control Centre (SCC) (see Figure 15d), is equipped with all the high tech services which facilitate online screening of data monitored at various locations in the city environment and the online status of LED systems installed in the city. It has a Central AQMS server, a highly sophisticated customized software which receives and transfers data to the Master FTP server from where all information gets disseminated through the WEB portal, LED system, Mobile Application and IVRS. The SCC is equipped with a Basel Display combination of 6 LCD units that enable the scientists at IITM to monitor the health of instruments, sensors, network communication, etc. for all SAFAR cities from one point.

The SCC also houses a special lounge for scientists and VIP's from where they can see not only the entire SAFAR Network from one place, but also they can view the graphical representation of the analyzed data in the form of maps, models, etc. To encourage the young students and research fellows, to make them aware of the current research happenings and to develop their interest in research related to atmospheric sciences, a separate section is maintained in the SAFAR Control Centre from where these young minds can have a glimpse of the SAFAR research.

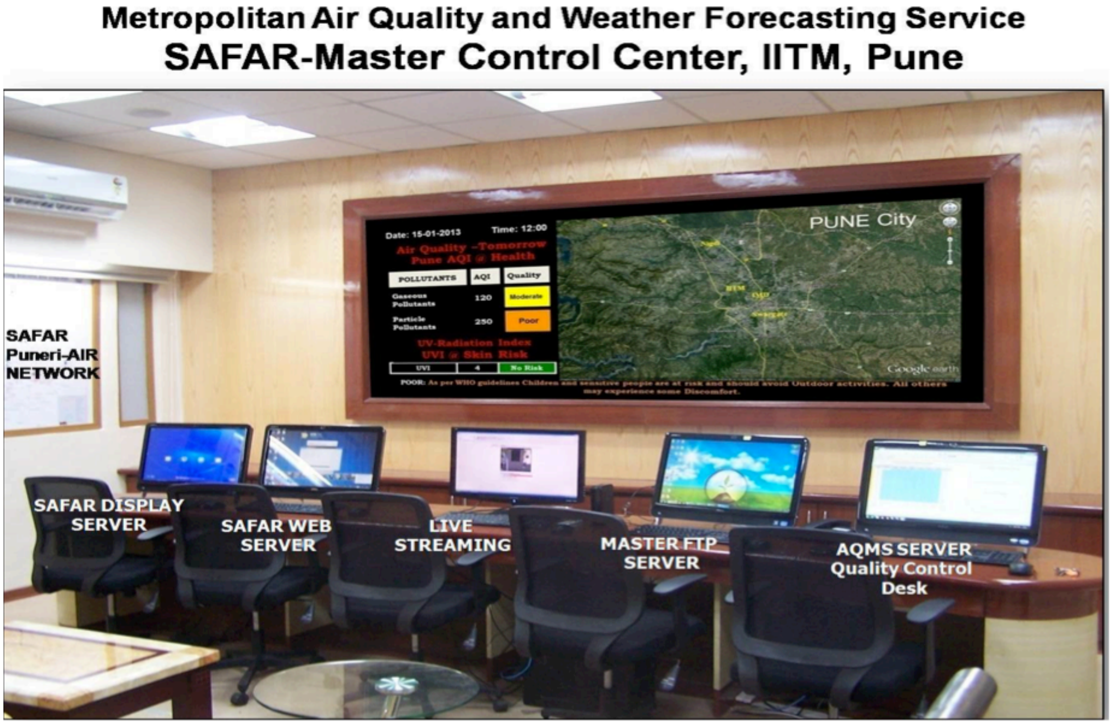


Figure 15d. SAFAR master control centre, IITM, Pune

7.4 Data collection

Section 4 describes the conceptual framework of SAFAR; the data is collected using a GPRS network in near-real-time as online raw data from ten stations and transferred to the AQMS server through the general packet radio service (GPRS) network. The raw data is then converted into a public friendly format such as AQI or UV-Index. It is finally archived into the FTP Master Control Server with wired connectivity, where data is also quality assured and quality controlled by the expert scientific team right away. This data set is then available for dissemination and to generate information products. The air quality forecasting data is available 24-72 hours in advance from the HPC facility of IITM to the FTP master control server. The FTP master control server channels the data to the Display Server from where it is converted to user-friendly products and then the required product information is transmitted to various LED display boards around NCT via a 3G communication network. The FTP server also caters the data to the SAFAR web server and to various service providers such as IVRS and media.

The analyzers operate around the clock and the data is recorded and stored at five-minute intervals for quality checks and scientific analysis. The data is subsequently averaged to 1-hour intervals. Calibration of the online analyzers is performed at the appropriate time intervals using inbuilt calibrators for some pollutants, or with external calibration cylinders with multipoint calibration techniques for others. Besides these data, meteorological parameters such as temperature, rainfall, humidity, wind speed, and wind direction are also monitored using AWSs.

8. AIR QUALITY FORECASTING MODEL

Air quality forecasting is a highly specialized area. Depending on application, it can require huge computational power on a regular basis. To forecast the air quality of various pollutants along with weather parameters, IITM uses in its atmospheric chemistry transport model a four nested domain, starting from near global to the local city level covering the city and the neighbouring region. The inner domain has a resolution of 1.67 km x 1.67 km which means that we can get the information of air quality at each 1.67 km grid interval. All these four domains will run interactively and feedback of meteorology to chemistry and vice-versa will be accounted for. This model requires several key inputs for accurate forecasting. The initial and lateral boundary conditions for the outermost domain in the meteorological model will be taken either from NCEP reanalysis or from internally generated coupled forecast system (CFS) of the National Centre for Medium Range Weather Forecasting (India) (NCMRWF), Noida, whereas for the chemical forecast model, it will be taken from MACC (Monitoring Atmospheric Composition and Climate), a project of the European Union, under the MoU between IITM and EU- project partners.

The air quality forecasting is being carried out by involving a number of "simultaneously interactive components" hence it is called a system (SAFAR) rather than a model. The major components of SAFAR are:

(1) Meteorological Model
(2) Emission Model
(3) Atmospheric Chemistry Transport Model

For SAFAR-Delhi, two independent AQ forecasting systems were used for redundancy, developing confidence and quality assurance. The components of the systems are:

SYSTEM-1:
(A) Meteorological Model - WRF
(B) Emission Model - GIS based Statistical Model (EGIS)
(C) Atmospheric Chemistry Transport Model - WRF-CHEM
Complete System: WRF - CHEM-EGIS

SYSTEM-2:
(A) Meteorological Model - WRF
(B) Emission Model - GIS based Statistical Model (EGIS)
(C) Atmospheric Chemistry transport Model - CMAQ
Complete System: WRF-CMAQ-EGIS

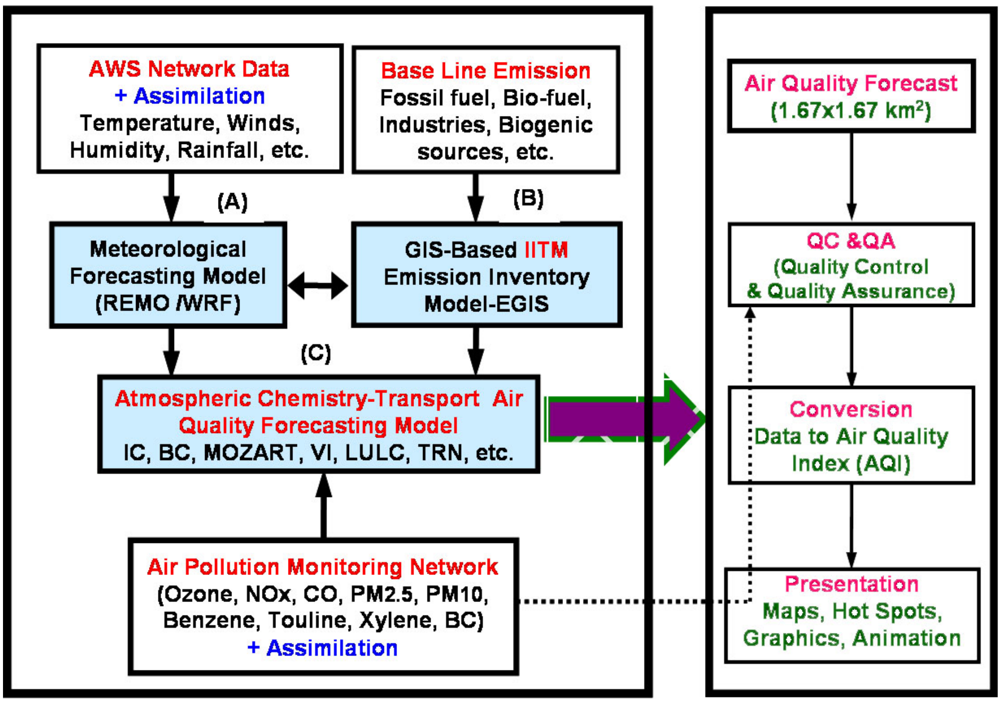


Figure 16. Flow chart of air quality and weather data collection and information dissemination

The flowchart is depicted in Figure 16. The AWS network data and subsequent assimilation provides the necessary input to the meteorological forecasting model (A). The output of (A) is used as input for (C). The base line emission data which is generated by IITM is used along with available secondary data, and then it is geo-referenced and gridded using the GIS model (B). The output of (B) is also used as an input for (C). The air pollution monitoring data from the network of 10 stations is assimilated and used as input to (C). The atmospheric chemistry transport model (C) acts as the heart of the system and finally provides the air quality in real time as well as its forecasting (24-72 hours in advance) with 1.67 km x 1.67 km grid resolution for the domain covering the NCT region of Delhi. The box on the right is related to post processing and for conveying the information to the common public.

8.1 Different inputs to the model

Emission inventory input

As discussed earlier detailed emission sources and different types of pollutants are taken into account from the study area with the help of the emission inventory. This is a critical model input.

Surface library: physiographic features

As a GIS based model is used, surface topography is important input for the model. Delhi lies almost entirely in the Gangetic plains. It is surrounded by prominent geographical features such as the Great Indian Desert to the west, Alwar hills to the southeast, Mewat plain to the south and Ganges river valley to the east. It consists of two major geographic divisions, the Yamuna flood plain and the Delhi ridge.

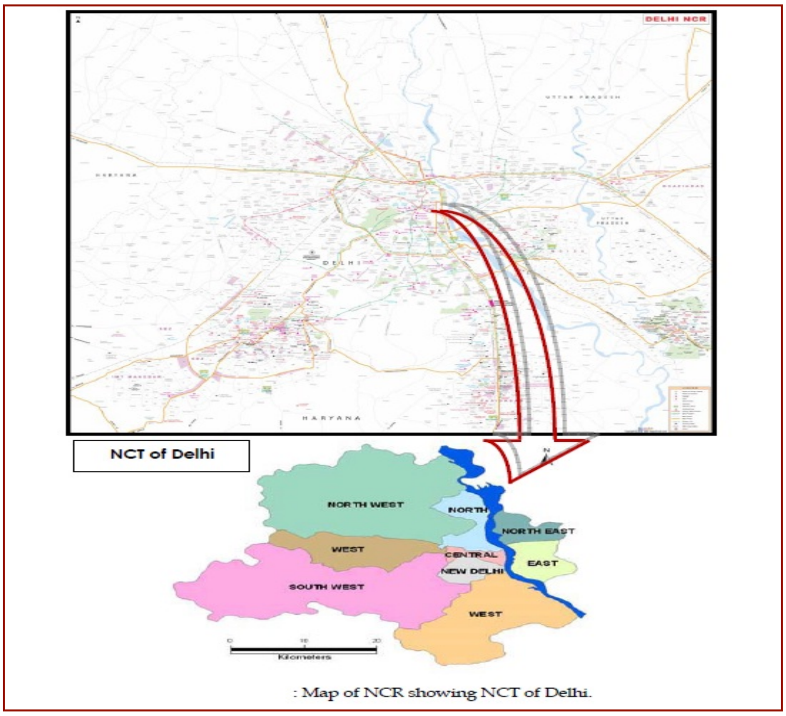


Figure 17a. Map of NCR showing NCT of Delhi

Assimilation of data

A continuous data input for the entire study area is very important for model analysis. The available air quality data is processed, interpolated for points where data is not available, using a specific technique, and a uniform data sheet is generated with the resolution of 1.67km×1.67km. Such input is given to the model.

8.2 Forecast modelling and supercomputing

Air quality forecasting is a highly specialized area requiring very high computational power for sophisticated modelling on a regular basis. The complex computer model which handles millions of calculations in seconds provides the required tool in SAFAR for focusing on the city area with high resolution (Figure 17b).

Figure 17b. Fastest supercomputer at IITM, Pune

9. DISSEMINATION OF INFORMATION TO THE PUBLIC

The outcome of the air quality model, i.e. the forecast, and current information of air quality and weather parameters will be translated into the AQI developed specifically for India. This translated information will be provided to the common public via different media sources. A separate network of display stations has been established with LED screens; 24x7 current and forecasted AQI along with weather conditions is displayed along with associated health advisories through the network and detailed information is made available on the web portal www.safar.tropmrt.res.in. In case of emergency conditions, for public awareness, information will be given via radio/TV and e-mail, and an SMS alert service will be activated for registered users. An IVRS system is made available through which people can get all the information by just calling a toll free number.

9.1 Products

(1) **Air Quality**

- Location specific current and 1-3 days advance air quality forecasting
- Air pollution maps generated at 1.5 km x 1.5 km resolution at city level.

(2) **Weather**

- Location specific current and 3 days advance weather forecasting
- Weather Maps generated at 3 km x 3 km resolution at city level, 3-6 hour forecast-nowcasting.

(3) **Harmful Solar Radiation**

- Location specific current UV-index information at city level (new feature added for Pune).

(4) **Emission Scenario**

- Generating emission loads by various pollution sources at 1km x 1km resolution at city level.

9.2 Product Parameters

(a) **Air pollutants**

- Particulate Matter (PM_{10}, $PM_{2.5}$)
- Hg (Mercury)
- O_3 (Ground level ozone)
- NO_X (Oxides of Nitrogen)
- CO (Carbon Monoxide)
- BC (Black Carbon)
- OC (Organic carbon)
- Hydrocarbons- benzene, toluene, xylene

(b) **Weather parameters**

- Temperature
- Rainfall
- Humidity
- Wind speed and direction
- Ultraviolet radiation

9.3 Conversion of data to information

(a) Severity of pollution in colour codes (green to maroon)
(b) Text and advisories with severity (Good to Unhealthy or Critical)
(c) Severity of pollution via AQI (on the scale of 0-500)
(d) Emission scenario of the city from anthropogenic sources at 1 km x 1 km resolution
(e) SMS alerts on extreme air quality and weather conditions
(f) Dynamic Web-Portal – online Air-Now and Air-Tomorrow service with weather
(g) Severity of UV radiation for skin via UV-Index (on scale of 1-10)

9.4 Benefit to end user

(a) Protecting human health
(b) Planning of agricultural crop yield
(c) Awareness of the impact of air quality and weather
(d) Basis for mitigation strategies to protect human health

9.5 Outreach

It is important to spread awareness regarding severity of air pollution problems to the common public. Thus, the outputs of the project are provided in a citizen friendly format. Once people know about the availability of such products this will in turn sensitize and build awareness of the importance of these issues with the decision members, and further the utilization of air quality information for mitigation measures, which serves the actual purpose. Therefore, it is important to popularize the concept and educate the public for which several interactive sessions are planned along with lectures and hands-on training.

Measures taken by IITM to spread the awareness and project outputs are discussed below.

9.5.1 *Web portal and other forms of dissemination*

The SAFAR Programme is providing timely and accurate air quality information so that citizens can make informed decisions regarding their health. The public can access the AQI and air quality forecasts via a web portal, or by calling the SAFAR air quality information Integrated Voice Response Service (IVRS) toll-free number (English, Hindi and regional language recording). Interested citizen can obtain information via e-mail and can contact safar@tropmet.res.in. The AQI values for current time and 24-72 hour advance forecast for different parts of the city will be reported, in near real-time, on the SAFAR website http://safar.tropmet.res.in (see Figure 18) updated hourly, 24-hours, and seven days a week. Air quality information of the city in near-real-time is also available on public display systems. The information is updated every hour to highlight the variability and to provide the most current air quality conditions.

Figure 18. Display website

9.5.2 *Display network*

Model output of the 24-72 hour advance forecast and current AQI values are transmitted to the display server and displayed on the display boards at 14 locations in simple public friendly format. Since SAFAR Delhi was launched at the time of CWG, 2010, some of the display boards were arranged inside the sports complex for the benefit of the participants of CWG, 2010. These display boards are now relocated to other important locations in the NCT, the list of digital displays in NCT with the map is given in Figure 19 and examples of two display screens are shown in Figure 20.

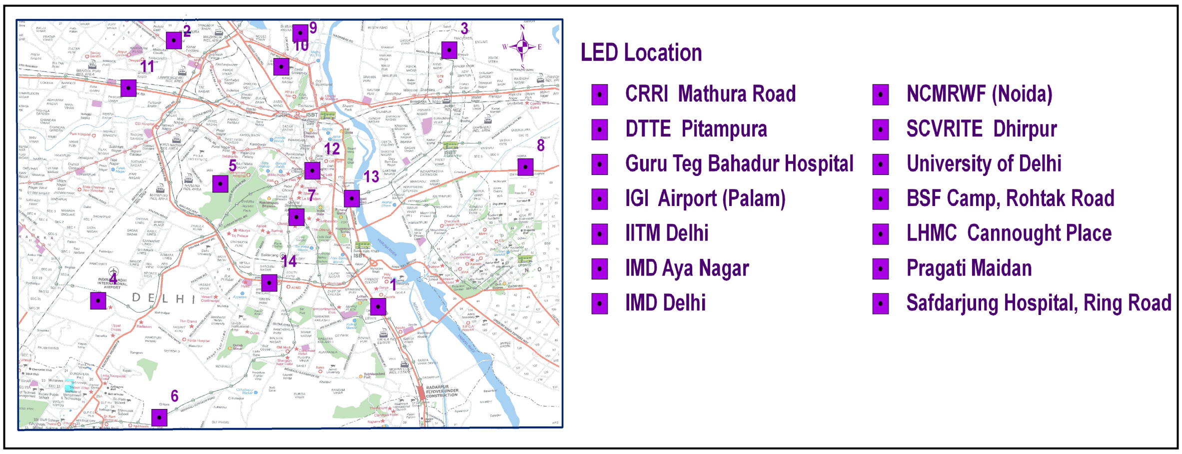


Figure 19. Display stations network in NCT

Figure 20. LED/LCD display screens

9.5.3 Interactive Voice Response Service

The Interactive Voice Response Service (IVRS) is a technology that automates interactions with telephone callers. IVRS solutions will enable users to retrieve information on SAFAR from any telephone. We intend to develop an IVRS that enables a person to make a selection from a voice menu to know about the current and forecasted air quality and weather information in a particular location within the city. The selection is made using touch-phone keypad entries or voice responses. The phone system plays pre-recorded voice prompts and the person typically presses a number on a telephone keypad to select the option associated with the voice prompt as per the information required, which will be updated hourly based on the SAFAR products. The public can access the AQI and air quality forecasts via IVRS by calling a toll-free (English, Hindi and regional language recording) phone number (+91- 1800 1801 717) to get information for the city and city outskirts.

9.5.4 Mobile application

The Indian Institute of Tropical Meteorology based in Pune has developed for SAFAR an app to help assess the air quality of the national capital and produce associated health advisories. The Mobile Application (Figure 21) has been launched for the first time in the country. This application can be downloaded for free. It will provide air quality, weather and UV radiation information at the same time at any location. This application can be used in all smart phones. Citizens can now access real time air quality information and have information available at their fingertips. The app is active for Delhi and Pune and will be scaled up for other metro cities like Mumbai and Ahmedabad soon.

Figure 21. Screen shot of mobile application

10. SOME RESULTS AND FORECAST VERIFICATION

A comparison of one-day forecasts provided using WRF-Chem simulations along with the 24-hour mean $PM_{2.5}$ and PM_{10} observations at one of the stations, namely Major Dhyanchand National Stadium (MDNS) site, is shown in Figure 22. It should be noted that during and after CWG-2010, the prevalence of low wind conditions, temperature inversion and formation of a relatively stable and persistent boundary layer played a vital role in the slower dispersion of air pollutants and hence the observations are dominated by localized emissions with advection of pollutants from other regions playing a smaller role. The emissions inventory was not changed in the model, even though some air pollution control measures were applied during the Games. This was in order to study whether there was indeed a reduction in the concentrations, which would be indicated by the model continually over predicting the particulate matter during CWG-2010.

The WRF-Chem output indicates that meteorology played a major role in the absolute mass concentrations of particulate matter throughout the entire study period. There was heavy rainfall before CWG-2010 that caused reduction of particulate matter due to wet deposition and is captured well by the model (Figure 22). The modelled increase in PM_{10} and $PM_{2.5}$ after the rain period also matches the observations indicating that the large decrease in emissions, expected at the start of the CWG-2010 period did not occur. Indeed, the observations show even larger values than the model estimates. During the middle of the games period, there was a sudden reduction in particulate matter which slowly recovered towards the end of CWG-2010. During this period, the model predicts considerably higher particulate matter than observed. This could be the result of total restriction of traffic around the MDNS site for the road cycling event.

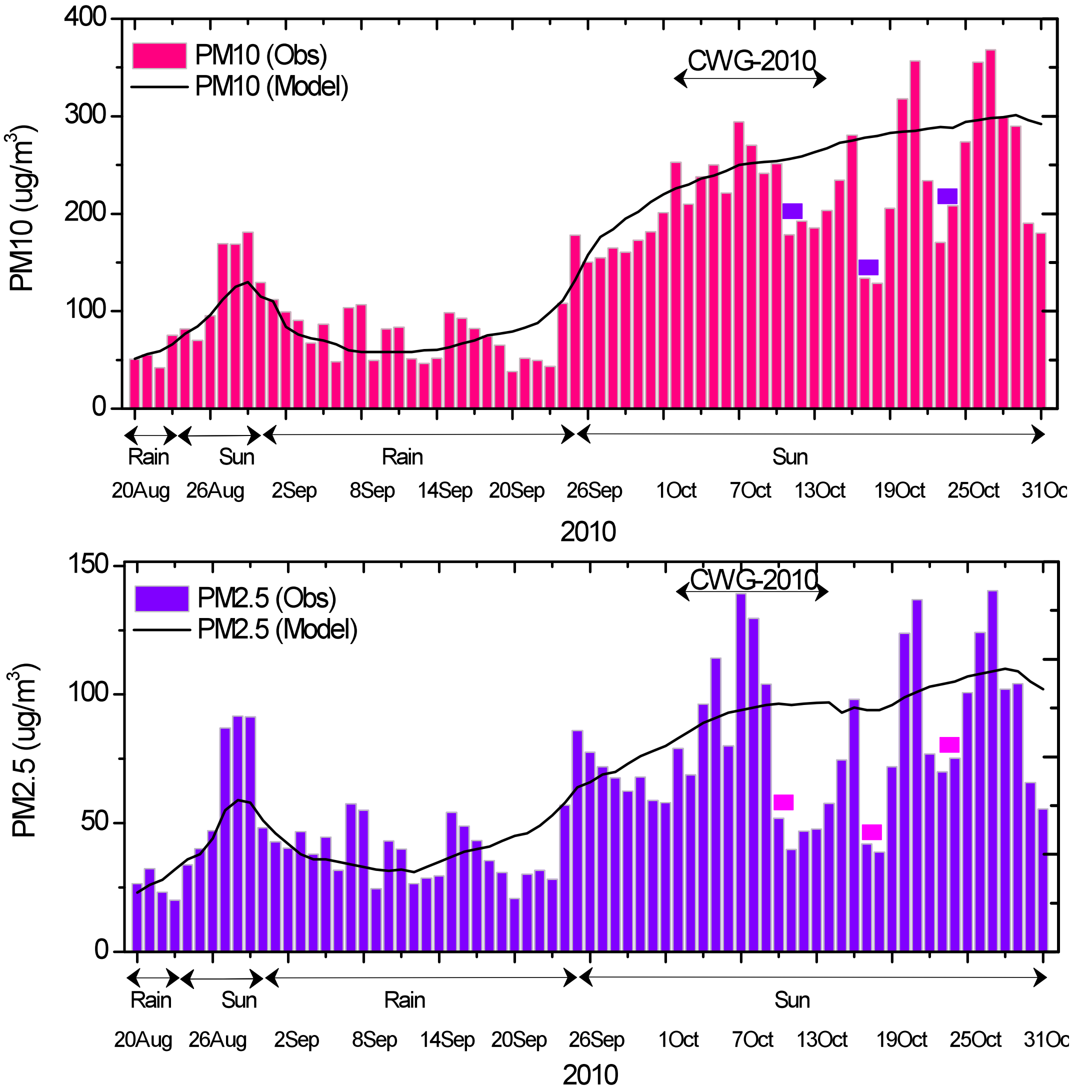


Figure 22. Variation in PM_{10} (top panel) and $PM_{2.5}$ (bottom panel) at the MDNS site in Delhi before, during and after the CWG-2010 . The black lines indicate the WRF-Chem simulations without considering the reductions in emissions during the Games. The pink/blue dashes indicate Sundays to highlight the intra weekly change. (Beig et al. *Atm. Env.* 2013)

11. SOCIO-ECONOMIC BENEFITS OF SAFAR

11.1 AQI for public reporting and proposing new concept for India

As a result of economic liberalization, started on 24 July 1991, India became one of the world's fastest growing economies by 2008. Presently, the economy of India is the ninth largest in the world by nominal Gross Domestic Product (GDP) and the third-largest purchasing power party (PPP). Moreover, the country is one of the G-20 major economies and member of BRICS which is an association of five major emerging national economies, Brazil, Russia, India, China and South Africa.

Although during past decades rapid economic growth has brought many benefits to India, it has imposed notable adverse impacts on the local and regional air quality and other environmental parameters. The economic and social development in India is reflected in the rapid growing industrialization, urbanization, increased transportation, etc. which on the other hand is putting the

1.27 billion population at the risk of heart and lung diseases by altering the normal composition of air. In a recent study it has been recognized that the annual cost of environmental damage to India is around $ 80 billion, equivalent to 5.7% of the country's GDP. Outdoor air pollution is one of the major environmental issues which accounts for 28 % of total cost of environmental damage, followed by indoor air pollution (23%), crop lands degradation (19%), water supply, sanitation and hygiene (14%), pastures degradation (11%) and forest degradation (4%). A recent survey shows India ranked 126th overall and last in the air pollution effects on human health among 132 countries. Medical studies reveal that the long term exposure to air pollution increases the risk factor of getting a stroke and the number of people suffering from heart diseases. It has been estimated that if India could reduce air pollution by 10% then the savings from reduced health damages would come to $24 billion and if it could reduce air pollution by 30% then India can save substantially higher health savings of $105 billion (World Bank Report, June 2013). In India, the problem of air pollution is more intense particularly in metropolitan regions like Delhi, Mumbai, Chennai, Kolkata, Hyderabad, Bangalore, Ahmadabad and Pune due to the high population and high vehicle number.

To reduce the cost involved in the damage caused by air pollution episodes and extreme weather conditions and associated risks to human health and agriculture, a robust early warning system should be designed and implemented. This requirement has been fulfilled by the project System of Air Quality Forecasting & Research (SAFAR). System products developed under the project can lead to numerous social and economic benefits, including cost savings in different sectors like health, agriculture, aviation, tourism, infrastructure and many others which directly or indirectly get affected by air quality and weather, and also helps to improve disaster management skills as has already been demonstrated by the project. The information provided by the project can also be used by decisionmakers to implement appropriate long-term and short-term mitigation strategies and to develop new sustainable policies.

11.2 Converting data to information

The path from generating raw data to decisions that generate social and economic benefits is complex and needs scientific understanding and linkages with socioeconomic aspects at each step. Most essential part of this project was to design system products in such a way that it will help in decisionmaking and give maximum social and economical benefits. This process is complex and involves round the clock measurements of various air quality indicators and weather parameters, analyzing the same with basic scientific knowledge, improving forecasting capabilities with basic scientific research, translating science to information and disseminating the information in very simple and user-friendly formats so that maximum number of stakeholders, including government agencies, educational institutes and the common public, can understand and use the same.

The process of converting science to useful applications is very crucial and important, for this purpose the concept of AQI and UV Index (UVI) has been introduced in the project. AQI is a rating scale used for reporting the quality of air we breathe in and the associated health effects, whereas, UVI is a measure of the amount of skin damaging UV radiation expected to reach the earth's surface at the time when the sun is highest in the sky (around midday). AQI and UVI provide information in terms of colour and codes which can be easily understood by the common public. There are health and skin advisories associated with each colour code which helps the public to take first hand preventive measures, which will minimize the direct costs involved in drug treatment, hospitalization, Intensive Care Unit (ICU) management and indirect costs due to loss of productivity and working days. The dissemination of information is of great importance, without this no one can use the system products to extract maximum benefits and hence various user-friendly platforms have been developed under the project as described in above sections.

11.3 System products and socioeconomic benefits

Following are the system location specific products which get updated at each hour to promote understanding of the variability and to provide most recent air quality and weather conditions in the region. Moreover, alert networks have been established, which generate e-mail alerts and SMS alerts for extreme weather conditions or air pollution events.

(1) Air Quality- Now
(2) Air Quality-Tomorrow
(3) Weather-Now
(4) Weather-Tomorrow
(5) UV Index –Skin Advisory
(6) Air Quality Index (AQI) - Health Advisory
(7) City Pollution Maps

The products generated will provide valuable information on current and 1-2 days advance forecast for air quality and weather, harmful radiation and emission scenarios over the city area in a very simple and user-friendly format, which helps to reduce impacts and assist policy makers and the common public in decisionmaking. Air Quality Now, Weather Now and information of current UV radiation in terms of UVI helps to reduce first hand impacts of deteriorated air quality and harmful UV radiation on human health, agricultural crops, etc. On the other hand, Air Quality and Weather forecast, associated alerts and city pollution maps, help in designing action plans to minimize future impacts which directly or indirectly lead to socioeconomic development in the region. Some of the major sectors which get benefits from the project are listed below.

- **Protecting human health**

System products help to reduce first hand impacts of deteriorated air quality on human health and effects of harmful solar radiation on the skin, reducing the costs involved in health damage, which on the other hand improves the productivity of the region by helping to prevent a large number of the population from adverse effects of pollution.

- **Planning of agricultural crop yield benefit**

The system products can be used for crop management, irrigation decisions, preventing weather related diseases, reducing impacts of harmful gaseous and particulate pollutants, like ozone and particulates, on crop yield. It will help farmers to plan future crop yields, leading to reduced uncertainty about yield and prices. In terms of economy it will help to plan sustainable utilization of scarce resources and minimize fluctuations in prices of agricultural products.

- **Aviation activity**

System products will help to optimize flight patterns by providing weather and air quality forecasts which can reduce operational costs at airports, improve safety and help passengers to manage their time.

- **Administering forest, protected areas in the city**

City pollution maps can help the government to manage protected areas in the city, defining areas for tree plantation, so as to give maximum benefits at required locations and to improve scheme benefits.

- **Disaster management**

System products help to improve disaster management skills in the city and lower the costs related to extreme weather events like flood, strong winds, air pollution events, etc. The products also help society to safeguard in advance.

- **Tourism**

System products will help to improve tourism in the region which will eventually lead to local economic development and improving life style in the region.

- **Infrastructure development and planning**

As infrastructure development depends on weather conditions, system products will help to strategically manage and plan developmental projects in such a way that operational costs involved in the project can be minimized.

- **Awareness on Impact of Air Quality and Weather**

Air Quality and Weather forecast, associated alerts and city pollution maps helps in designing action plans to minimize future impacts which directly or indirectly leads to socioeconomic development in the region. System products are of economic value and help to improve awareness and implement air quality management programs to reduce emissions of various air pollutants.

As we know, the effects of criteria pollutants on human health, when exceeding the set limits, are different for different age groups and according to the general health of the human, sensitivity to the pollutants differ. There are many cases of increases in hospital visits when the safe limit for the particulate matter is exceeded to a certain level, particularly during winter. However, it has not been noticed for other criteria pollutants, unless it exceeds the safe limit marginally. Therefore, it is strongly felt that instead of reporting overall air quality using above three presenting criteria, reporting AQI for individual criteria pollutants would be more informative for the general public for taking preventive measures to protect themselves from ill health. Another important advantage of this reporting method is that it gives an idea about mitigation strategies to be adopted based upon severity of the individual criteria pollutant and associated major sources. Moreover, it also allows us to provide a balanced picture about the air quality ranging from Good to Unhealthy and showcases both sides of the coin. This concept which is quite significant in Indian context and has been presented to the Scientific Advisory Group (SAG) of the Global Atmosphere Watch (GAW) Urban Research Meteorology and Environment (GURME) of WMO which deals in the related aspects and has expressed its appreciation to this effort.

It has to be mentioned here that under the project the attempt has been made to develop system products which are of economic value and help to improve awareness and implement air quality management programmes to reduce emissions of various air pollutants. The project will help to achieve "Faster, more inclusive and sustainable growth" which India has committed to during its 12^{th} five year plan (2012-17) (Planning Commission, Government of India 2013) by giving valuable information regarding air quality, weather and harmful UV radiation, which will help to reduce total costs of environmental damages.

12. FUTURE PLANS

SAFAR system was dedicated to the nation as "SAFAR-Delhi" on the occasion of the 19th Commonwealth Games, 2010, hosted in Delhi. For the first time India conceived a system for air quality forecasting and Delhi became the first city in the country providing 24-72 hour forecast for criteria pollutants. Now India is among the few developing nations to take a big leap in this area of environmental research applications and services. SAFAR-Delhi provided the air quality information on daily basis at the venue of the Games and other various key locations in Delhi through wireless digital display panels. The information displayed was found to be of great help to the athletes and citizens. It will continue to provide its services for Delhi NCT region.

After the success at Delhi, implementation in following metropolitan cities of India has been recommended by WMO GURME: Pune, Mumbai, Ahmedabad, Chennai and Kolkata. Pune is the next chosen city where the SAFAR project is implemented by the name of "Puneri-Air". It integrates several complex components like an air pollution monitoring network at 10 different locations in the Pune Metropolitan Region (PMR), 20 integrated automatic weather stations, a high-resolution emission inventory, activity data and a 3-D coupled atmospheric chemistry transport modelling system within PMR (in an area of 40x40 km in its centre) to facilitate current and forecasted information of major criteria air pollutants, weather parameters and UV-Index. The obtained data is being disseminated in terms of meaningful information for the common citizen with digital display boards at 12 crucial locations in PMR and through various media devices.

13. TECHNICAL REPORTS PUBLISHED

Within SAFAR several publications have been made. Here we like to highlight the work on the development of the AQI (Figure 23) and the emissions inventory report (Figure 24). This former one was released on 23rd September 2010 by the Ministry of Earth Sciences and became the first authentic report for AQI published. For the first time, the air quality in Delhi is shown with colour codes.

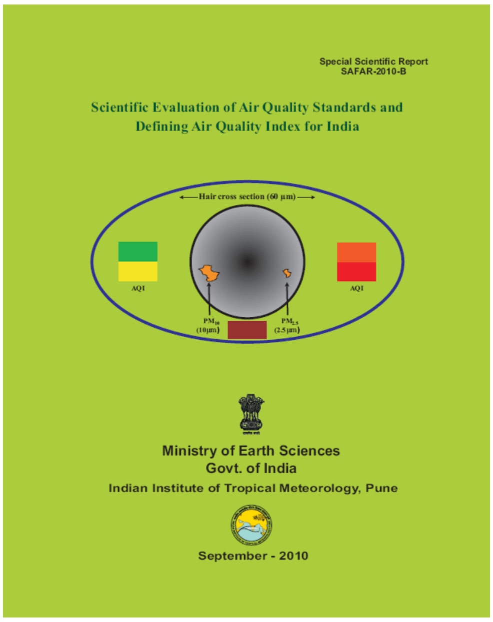


Figure 23. Cover page depicting the Report on Development of Air Quality Index for India

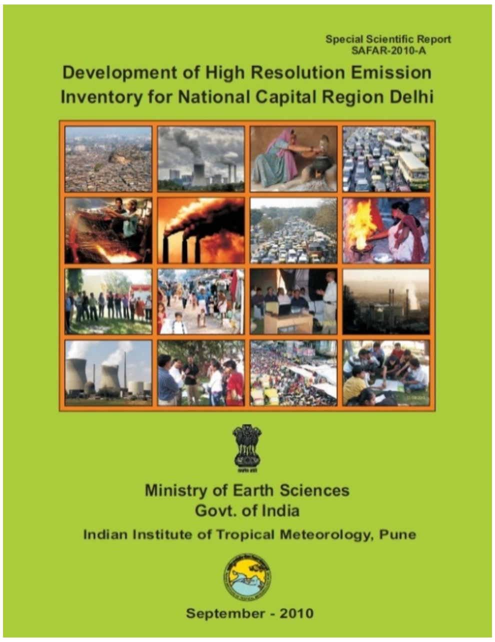


Figure 24a . Cover page depicting the SAFAR mission inventory

Figure 24b. Inauguration of emission inventory report

The latter report was released also on 23rd September 2010 by Ministry of Earth Sciences.
A comprehensive study based on the scientific knowledge has been made to develop the high-resolution (1.67 km x 1.67 km) emission inventory of all major air pollutants for a domain of ~65 km×70 km (~4500 km^2 area) covering Delhi and its adjacent region to facilitate accurate air quality forecasting. Emission inventories have been developed for eight air pollutants as mentioned in this report.

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REFERENCES

Avol, E.L., W.C. Navidi, E.B. Rappaport and J.M. Peters, 1998: *Acute effects of ambient ozone on asthmatic, wheezy, and healthy children*, Res. Rep. 82(III), Health Eff. Inst., Boston, Mass., USA, 1-18.

Badhwar, N., R.C. Trivedi and B. Sengupta, 2006: Air Quality status and trends in India. *Indian Journal of Air Pollution Control*, 6, 71-79.

Barman, S.C, N. Kumar, R. Singh, G.C. Kisku, A.H. Khan, M.M. Kidwai, R.C. Murthy, M.P.S. Negi, P. Pandey, A.K. Verma, G. Jain and S.K. Bhargava, 2010: Assessment of urban air pollution and its probable health impact *Journal of Environmental Biology*, 31(6) 913-920.

Beig, G. et al., 2010: *Scientific Evolution of Air Quality Standards and Defining Air Quality Index for India,* Special Scientific Report SAFAR-2010-B, Ministry of Earth Sciences (Govt. of India), September 2010.

Beig G. and S. Gunthe, 2004: *Towards Characterizing Air Quality Standards for Ozone in India,* ENVIS-Newsletter, Jan-April, Vol 2, Issue 1.

Beig, G. and G.P. Brasseur, 2006: Influence of anthropogenic emissions on tropospheric ozone and its precursors over the Indian tropical region during a Monsoon, *Geophysical Research Letters*, 33, L07808, doi:10.1029/2005GL024949.

Beig, G., D.M. Chate, S.D. Ghude, A.S. Mahajan, R. Srinivas, K. Ali, S.K. Sahu, N. Parkhi, D. Surendran and H.R. Trimbake, 2013: Quantifying the effect of air quality control measures during the 2010 Commonwealth Games at Delhi, India, *Atmospheric Environment*, 80, 455-463.

Bishoi, B. Amit Prakash, V.K. Jain, 2009: *A Comparative Study of Air Quality Index Based on Factor Analysis and US-EPA Methods for an Urban Environment Aerosol and Air Quality Research*, Vol. 9, No. 1, pp. 1-17.

Brandon, C. and K. Hommann, 1995: *The Cost of Inaction: Valuing the Economy-wide Cost of Environmental Degradation in India,* October 17 (1995). Mimeo. Asia Environment Division, The World Bank, Washington D.C.

Central Pollution Control Board (CPCB), 2000: *Air quality status and trends in India* NAAQMS/14/1999-2000, Central Pollution Control Board, Ministry of Environment & Forests, Government of India, New Delhi, 163 pp.

Central Pollution Control Board (CPCB), 2003: *Ambient air quality statistics for Indian metro cities*. Central Pollution Control Board, Zonal Office, Bangalore.

Central Pollution Control Board (CPCB), 2008: *Epidemiological Study on Effect of Air Pollution on Human Health (Adults) in Delhi,* Environmental Health Series: EHS/1/2008, Ministry of Environment and Forests, Govt. of India. Aug 2008.

Dalvi, M., G. Beig, U. Patil, A. Kaginalkar, C. Sharma and A.P. Mitra, 2006: A GIS based methodology for gridding large scale emission inventories: Application to carbon-monoxide emissions over Indian region, *Atmospheric Environment*, 40, 2995, doi: 10.1016/j.atmosenv.2006.01.013.

Delfino R.J., R.S. Zeiger, J.M. Seltzer and D.H. Street (1998): Symptoms in pediatric asthmatics and air pollution: differences in effects by symptom severity, anti-inflammatory medication use and particulate averaging time. *Environmental Health Perspectives*, 106:751-761.

Ghude, S.D., S. Fadnavis, G. Beig, S.D. Polade and A.R.J. Van Der, 2008: Detection of surface emission hot spots, trends and seasonal cycle from satellite-retrieved NO2 over India, *Journal of Geophysical Research*, 113, D20305, doi: 10.1029/2007JD009615.

Jayaraman, G.N., 2007: Air quality and respiratory health in Delhi. *Environmental Monitoring and Assessment*, doi: 10.1007/s 10661-007-9651-0.

Katsouyanni K., G. Touloumi, E. Samoli, A. Gryparis, A. Le Tertre, Y. Monopolis, G. Rossi, D. Zmirou, F. Ballester, A. Boumghar, H.R. Anderson, B. Wojtyniak, A. Paldy, R. Braunstein, J. Pekkanen, C. Schindler and J. Schwartz, 2001: Confounding and effect modification in the short-term effects of ambient particles on total mortality: Results from 29 European cities within the APHEA2 project. Epidemiology 12:521-531.

Kaushik, C.P., K. Ravindra and K. Yadav, 2006: Assessment of ambient air quality in urban centres of Haryana (India) in relation to different anthropogenic activities and health risk. *Environmental Monitoring and Assessment*, 122, 27-40.

Kisku, G.C., R.P. Salve, M.M. Kidwai, A.H. Khan, S.C. Barman, R. Singh, D. Mishra, S. Sharma and S.K. Bhargava, 2003: A random survey of ambient air quality in Lucknow city and its possible impact on environmental health. *Indian Journal of Air Pollution Control*, 3, 45-58.

Laheri et al., 2000: Chapter 6. Health Effects of Urban Air Pollution in India, Air Pollution Health and Environmental Impacts, Edited by Bhola R. Gurjar, Luisa T. Molina and Chandra S.P. Ojha, CRC Press 2010, Pages 165-201, doi: 10.1201/EBK1439809624-c6.

MoEF, Seventh Amendment Rules, 2009: Ministry of Environment and Forests Notification, New Delhi, India, REDGNO.D.L.33004/09, Nov. 16 2009.

Nagendra S. M,K. Venugopal and S.L. Jones, 2007: Assessment of air quality near traffic intersections in Bangalore city using air quality indices. Transportation research. Part D, Transport and environment, ISSN: 1361-9209 2007, vol.12, no3, pp. 167-176.

Parivesh, 2001: Air Pollution and Human Health, CPCB Publication, September 2001.

Pearson J.F., C. Bachireddy, S. Shyamprasad, A.B. Goldfine and J.S. Brownstein, 2010: Association Between Fine Particulate Matter and Diabetes Prevalence in the U.S. Diabetes Care, 33 (10): 2196 doi: 10.2337/dc10-0698.

Planning Commission, 2013: Government of India, Twelfth Five Year Plan (2012-2017) Volume I, SAGE Publications, India Pvt ltd. New Delhi.

Pope, C. A., R.T. Burnett, M.J. Thun, E.E. Calle, D. Krewski, K. Ito and G.D. Thurston, 2002: Lung cancer, cardiopulmonary mortality, and long-term exposure to fine particulate air pollution, *Journal of American Medical Association* 287, 1132-1141.

Rao, C.V.C., A.B. Chelani, K.M. Phadke, M.Z. Hasan, 2002: Formation of an air quality index in India. *International Journal of Environmental Studies* 59, 331-342.

Sahu, S. K., G. Beig and C. Sharma, 2008: Decadal growth of black carbon emissions in India, *Geophysical Research Letters*, 35, L02807, doi:10.1029/2007GL032333.

Sharma, M., R. Pandey, M. Maheshwari, B. Sengupta, 2003: Interpretation of air quality data using an air quality index for the city of Kanpur, India. *Journal of Environmental Engineering and Science* 2, 453.

Sharma, M., R. Pandey, M. Maheshwari, B. Sengupta, B.P. Shukla and A. Mishra, 2003a: Air quality index and its interpretation for the city of Delhi. Clean Air. *International Journal on Energy for a Clean Environment*, 4, 83-98.

Shukla, A., A. Nasim and S. Gangophadhyay, 2006: Mass and Number concentration of respirable particulate matter in the ambient environment of Delhi. *Indian Journal of Air Pollution Control*, 6, 44 -45.

Tiwari, T.N. and M. Ali, 1987: Air Quality Index for Calcutta and its monthly variation for various localities, *Indian Journal of Environmental Protection*, 7, 172-176.

US Environmental Protection Agency (USEPA), 1998: *National air quality and emissions trends report 1997,* Environmental Protection Agency, 454:R- 98-016.

US Environmental Protection Agency (USEPA), 2003: *Air quality index: a guide to air quality and your health,* Environmental Protection Agency, Office of Air Quality Planning and Standards, Research Triangle Park.

US Environmental Protection Agency (USEPA), 2008: *Air quality index: a guide to air quality and your health,* Environmental Protection Agency, Office of Air Quality Planning and Standards, Research Triangle Park.

WHO, 2005: *Air quality guidelines for particulate matter, ozone, nitrogen dioxide and sulfur dioxide, Global update 2005*, *Summary of risk assessment*, WHO, 2006.

WHO: http://www.who.int/topics/air_pollution/en/

Wong CM, R.W. Atkinson, H.R. Anderson, A.J. Hedley, S. Ma, P.Y. Chau et al., 2002: A tale of two cities: effects of air pollution on hospital admissions in Hong Kong and London compared, *Environmental Health Perspectives*, 110:67-77.

World Bank, 2013: *An analysis of physical and monetary losses of environmental health and natural resources,* Washington DC, World Bank.

LIST OF RECENT GLOBAL ATMOSPHERE WATCH REPORTS*

149. Current Activities of the Global Atmosphere Watch Programme (as presented at the 14th World Meteorological Congress, May 2003). (WMO TD No. 1168).

150. WMO/GAW Aerosol Measurement Procedures: Guidelines and Recommendations. (WMO TD No. 1178).

151. WMO/IMEP-15 Trace Elements in Water Laboratory Intercomparison. (WMO TD No. 1195).

152. 1st International Expert Meeting on Sources and Measurements of Natural Radionuclides Applied to Climate and Air Quality Studies (Gif sur Yvette, France, 3-5 June 2003) (WMO TD No. 1201).

156. Addendum for the Period 2005-2007 to the Strategy for the Implementation of the Global Atmosphere Watch Programme (2001-2007), GAW Report No. 142 (WMO TD No. 1209).

157. JOSIE-1998 Performance of EEC Ozone Sondes of SPC-6A and ENSCI-Z Type (Prepared by Herman G.J. Smit and Wolfgang Straeter) (WMO TD No. 1218).

158. JOSIE-2000 Jülich Ozone Sonde Intercomparison Experiment 2000. The 2000 WMO international intercomparison of operating procedures for ECC-ozone sondes at the environmental simulation facility at Jülich (Prepared by Herman G.J. Smit and Wolfgang Straeter) (WMO TD No. 1225).

159. IGOS-IGACO Report - September 2004 (WMO TD No. 1235), 68 pp, September 2004.

160. Manual for the GAW Precipitation Chemistry Programme (Guidelines, Data Quality Objectives and Standard Operating Procedures) (WMO TD No. 1251), 186 pp, November 2004.

161 12th WMO/IAEA Meeting of Experts on Carbon Dioxide Concentration and Related Tracers Measurement Techniques (Toronto, Canada, 15-18 September 2003), 274 pp, May 2005.

162. WMO/GAW Experts Workshop on a Global Surface-Based Network for Long Term Observations of Column Aerosol Optical Properties, Davos, Switzerland, 8-10 March 2004 (edited by U. Baltensperger, L. Barrie and C. Wehrli) (WMO TD No. 1287), 153 pp, November 2005.

163. World Meteorological Organization Activities in Support of the Vienna Convention on Protection of the Ozone Layer (WMO No. 974), 4 pp, September 2005.

164. Instruments to Measure Solar Ultraviolet Radiation: Part 2: Broadband Instruments Measuring Erythemally Weighted Solar Irradiance (WMO TD No. 1289), 55 pp, July 2008, electronic version 2006.

165. Report of the CAS Working Group on Environmental Pollution and Atmospheric Chemistry and the GAW 2005 Workshop, 14-18 March 2005, Geneva, Switzerland (WMO TD No. 1302), 189 pp, March 2005.

166. Joint WMO-GAW/ACCENT Workshop on The Global Tropospheric Carbon Monoxide Observations System, Quality Assurance and Applications (EMPA, Dübendorf, Switzerland, 24 – 26 October 2005) (edited by J. Klausen) (WMO TD No. 1335), 36 pp, September 2006.

167. The German Contribution to the WMO Global Atmosphere Watch Programme upon the 225th Anniversary of GAW Hohenpeissenberg Observatory (edited by L.A. Barrie, W. Fricke and R. Schleyer (WMO TD No. 1336), 124 pp, December 2006.

168. 13th WMO/IAEA Meeting of Experts on Carbon Dioxide Concentration and Related Tracers Measurement Techniques (Boulder, Colorado, USA, 19-22 September 2005) (edited by J.B. Miller) (WMO TD No. 1359), 40 pp, December 2006.

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* *(A full list is available at http://www.wmo.int/pages/prog/arep/gaw/gaw-reports.html)*

169. Chemical Data Assimilation for the Observation of the Earth's Atmosphere – ACCENT/WMO Expert Workshop in support of IGACO (edited by L.A. Barrie, J.P. Burrows, P. Monks and P. Borrell) (WMO TD No. 1360), 196 pp, December 2006.

170. WMO/GAW Expert Workshop on the Quality and Applications of European GAW Measurements (Tutzing, Germany, 2-5 November 2004) (WMO TD No. 1367).

171. A WMO/GAW Expert Workshop on Global Long-Term Measurements of Volatile Organic Compounds (VOCs) (Geneva, Switzerland, 30 January – 1 February 2006) (WMO TD No. 1373), 36 pp, February 2007.

172. WMO Global Atmosphere Watch (GAW) Strategic Plan: 2008 – 2015 (WMO TD No. 1384), 108 pp, August 2008.

173. Report of the CAS Joint Scientific Steering Committee on Environmental Pollution and Atmospheric Chemistry (Geneva, Switzerland, 11-12 April 2007) (WMO TD No.1410), 33 pp, June 2008.

174. World Data Centre for Greenhouse Gases Data Submission and Dissemination Guide (WMO TD No. 1416), 50 pp, January 2008.

175. The Ninth Biennial WMO Consultation on Brewer Ozone and UV Spectrophotometer Operation, Calibration and Data Reporting (Delft, Netherlands, 31-May – 3 June 2005) (WMO TD No. 1419), 69 pp, March 2008.

176. The Tenth Biennial WMO Consultation on Brewer Ozone and UV Spectrophotometer Operation, Calibration and Data Reporting (Northwich, United Kingdom, 4-8 June 2007) (WMO TD No. 1420), 61 pp, March 2008.

177. Joint Report of COST Action 728 and GURME – Overview of Existing Integrated (off-line and on-line) Mesoscale Meteorological and Chemical Transport Modelling in Europe (ISBN 978-1-905313-56-3) (WMO TD No. 1427), 106 pp, May 2008.

178. Plan for the implementation of the GAW Aerosol Lidar Observation Network GALION, (Hamburg, Germany, 27 - 29 March 2007) (WMO TD No. 1443), 52 pp, November 2008.

179. Intercomparison of Global UV Index from Multiband Radiometers: Harmonization of Global UVI and Spectral Irradiance (WMO TD No. 1454), 61 pp, March 2009.

180. Towards a Better Knowledge of Umkehr Measurements: A Detailed Study of Data from Thirteen Dobson Intercomparisons (WMO TD No. 1456), 50 pp, December 2008.

181. Joint Report of COST Action 728 and GURME – Overview of Tools and Methods for Meteorological and Air Pollution Mesoscale Model Evaluation and User Training (WMO TD No. 1457), 121 pp, November 2008.

182. IGACO-Ozone and UV Radiation Implementation Plan (WMO TD No. 1465), 49 pp, April 2009.

183. Operations Handbook – Ozone Observations with a Dobson Spectrophotometer (WMO TD No. 1469), 91 pp, March 2009.

184. Technical Report of Global Analysis Method for Major Greenhouse Gases by the World Data Center for Greenhouse Gases (WMO TD No. 1473), 29 pp, June 2009.

185. Guidelines for the Measurement of Methane and Nitrous Oxide and their Quality Assurance (WMO TD No. 1478), 49 pp, September 2009.

186. 14th WMO/IAEA Meeting of Experts on Carbon Dioxide, Other Greenhouse Gases and Related Tracers Measurement Techniques (Helsinki, Finland, 10-13 September 2007) (WMO TD No. 1487), 31 pp, April 2009.

187. Joint Report of COST Action 728 and GURME – Review of the Capabilities of Meteorological and Chemistry-Transport Models for Describing and Predicting Air Pollution Episodes (ISBN 978-1-905313-77-8) (WMO TD No. 1502), 69 pp, December 2009, electronic version - July 2009.

188. Revision of the World Data Centre for Greenhouse Gases Data Submission and Dissemination Guide (WMO TD No.1507), 55 pp, November 2009.

189. Report of the MACC/GAW Session on the Near-Real-Time Delivery of the GAW Observations of Reactive Gases, Garmisch-Partenkirchen, Germany, 6-8 October 2009, (WMO TD No. 1527), 31 pp. August 2010.

190. Instruments to Measure Solar Ultraviolet Radiation Part 3: Multi-channel filter instruments (lead author: G. Seckmeyer) (WMO TD No. 1537), 55 pp. November 2010.

191. Instruments to Measure Solar Ultraviolet Radiation Part 4: Array Spectroradiometers (lead author: G. Seckmeyer) (WMO TD No. 1538), 43 pp. November 2010.

192. Guidelines for the Measurement of Atmospheric Carbon Monoxide (WMO TD No. 1551), 49 pp, July 2010.

193. Guidelines for Reporting Total Ozone Data in Near Real Time (WMO TD No. 1552), 19 pp, April 2011 *(electronic version only).*

194. 15th WMO/IAEA Meeting of Experts on Carbon Dioxide, Other Greenhouse Gases and Related Tracers Measurement Techniques (Jena, Germany, 7-10 September 2009) (WMO TD No. 1553). 330 pp, April 2011.

195. WMO/GAW Expert Workshop on Global Long-term Measurements of Nitrogen Oxides and Recommendations for GAW Nitrogen Oxides Network (Hohenpeissenberg, Germany, 8-9 October 2009) (WMO TD No. 1570), 45 pp, February 2011.

196. Report of the Second Session of the CAS JSC OPAG-EPAC and GAW 2009 Workshop (Geneva, Switzerland, 5-8 May 2009) (WMO TD No. 1577).

197. Addendum for the Period 2012 – 2015 to the WMO Global Atmosphere Watch (GAW) Strategic Plan 2008 – 2015, 57 pp, May 2011.

198. Data Quality Objectives (DQO) for Solar Ultraviolet Radiation Measurements (Part I). Addendum to WMO/GAW Report No. 146 - Quality Assurance in Monitoring Solar Ultraviolet Radiation: State of the Art (*electronic version only*).

199. Second Tropospheric Ozone Workshop. Tropospheric Ozone Changes: observations, state of understanding and model performances (Météo France, Toulouse, France, 11-14 April 2011), 226 pp, September 2011.

200. WMO/GAW Standard Operating Procedures for In-Situ Measurements of Aerosol Mass Concentration, Light Scattering and Light Absorption (Edited by John A. Ogren), 134 pp, October 2011.

201. Quality Assurance and Quality Control for Ozonesonde Measurements in GAW (Prepared by Herman Smit and ASOPOS Panel), 95 pp. October 2014.

202. Workshop on Modelling and Observing the Impacts of Dust Transport/Deposition on Marine Productivity (Sliema, Malta, 7-9 March 2011), 50 pp, November 2011.

203. The Atmospheric Input of Chemicals to the Ocean. Rep. Stud. GESAMP No. 84/GAW Report No. 203. 69 pp. (ISSN: 1020-4873).

204. Standard Operating Procedures (SOPs) for Air Sampling in Stainless Steel Canisters for Non-Methane Hydrocarbons Analysis (Prepared by Rainer Steinbrecher and Elisabeth Weiß), 25 pp. September 2012.

205. WMO/IGAC Impacts of Megacities on Air Pollution and Climate, 309 pp. September 2012 (ISBN: 978-0-9882867-0-2).

206. 16th WMO/IAEA Meeting of Experts on Carbon Dioxide, Other Greenhouse Gases and Related Tracers Measurement Techniques (GGMT-2011), Wellington, New Zealand, 25-28 October 2011, 67 pp, October 2012.

207. Recommendations for a Composite Surface-Based Aerosol Network, Emmetten, Switzerland, 28-29 April 2009, 66 pp. November 2012.

208. WMO GURME Workshop on Urban Meteorological Observation Design, (Shanghai, China, 11-14 December 2011).

209. Guidelines for Continuous Measurements of Ozone in the Troposphere (Prepared by Ian E. Galbally and Martin G. Schultz), 80 pp, February 2013 (WMO-No. 1110, ISBN: 978-92-63-11110-4).

210. Report of the Third Session of the CAS Joint Scientific Committee of the Open Programme Area Group on Environmental Polllution and Atmospheric Chemistry (JSC OPAG-EPAC), (Geneva, Switzerland, 27-29 April 2011) (*electronic version only*).

211. Rationalizing Nomenclature for UV Doses and Effects on Humans (CIE209:2014/GAW Report No. 211) (ISBN: 978-3-902842-35-0).

212. Standard Operating Procedures (SOPs) for Spectral Instruments Measuring Spectral Solar Ultraviolet Irradiance, 21 pp. June 2014.

213. 17th WMO/IAEA Meeting on Carbon Dioxide, Other Greenhouse Gases and Related Tracers Measurement Techniques (GGMT-2013), (Beijing, China, 10 - 13 June 2013), 168 pp. July 2014.

214. Report of the GAW 2013 Symposium and the Fourth Session of the CAS JSC OPAG-EPAC, Geneva, Switzerland, 18-20 March 2013, 82 pp, October 2014.

215. Report of the First Session of the CAS Environmental Pollution and Atmospheric Chemistry Scientific Steering Committee (EPAC SSC), (Geneva, Switzerland, 10-12 June 2014), 32 pp. December 2014.

216. Seventh Intercomparison Campaign of the Regional Brewer Calibration Center Europe (RBCC-E), Lichtklimatisches Observatorium, Arosa, Switzerland, 16-27 July 2014, 106 pp. March 2015.