

Black Carbon Research Initiative

National Carbonaceous Aerosols Programme (NCAP) Science Plan

INCCA: INDIAN NETWORK FOR CLIMATE CHANGE ASSESSMENT



Ministry of Environment & Forests, Ministry of Earth Sciences, Ministry of Science & Technology and Indian Space Research Organization
Government of India

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Cover Picutre:

1. Multi-Wavelength Radiometer (MWR) is an instrument to measures direct solar radiation at 10 different wavelengths. This is a stand-alone micro processor controlled instrument automated to track the Sun from Sun rise to Sun set. Analysis of MWR data can provide spectral optical depths, which is a measure of aerosol loading in a cloud-free atmosphere
2. Wood Cook Stove

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Samudra Tapu glacier is located in Chandra river basin in Himachal Pradesh, India

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Foreword



I have great pleasure in introducing the document '**Black Carbon Research Initiative - Science Plan**' of the **National Carbonaceous Aerosols Programme** being devised under the aegis of the Indian Network of Climate Change Assessment (INCCA) that we launched last year. The issue of

'black carbon' and its relationship with climate change has gained enormous scientific and popular interest over the last few years. **India is well aware of the importance of the issue, and is committed to addressing it, based on sound scientific assessments.**

The knowledge and understanding on aspects such as vertical distribution and mixing of Black Carbon with other aerosols, effects of cloud cover and monsoon still remains uncertain and incomplete. There is thus a need to have better understanding on the following science questions:

- The contribution of black carbon aerosols to regional warming.
- Role of black carbon on atmospheric stability and the consequent effect on cloud formation and monsoon.
- Role of black carbon in altering the ability of hygroscopic aerosols to act as cloud condensation nuclei.
- Role of BC-Induced low-level temperature inversions and their role in formation of fog especially over northern India.
- Role of black carbon on Himalayan glacier retreat.

With the launch of INCCA in October 2009, I had announced a comprehensive study on Black carbon not only to enhance

the knowledge and understanding of the role of Black carbon in the context of global warming but also to address the sources and impacts of the black carbon on melting of glaciers. I had emphasised on 3Ms as the approach – Measure, Model and Monitor.

The Black Carbon research initiative builds on this approach and sets out the science programme and to respond to the scientific questions. The science plan has been developed through an intensive consultative process and with the involvement of experts in the subject and builds upon the work of ISRO, MoES and other experts. The initiative is visualised as an ambitious programme with the involvement of over 101 institutions with 60 observatories nationwide. The study would lead to:

- (a) Long-term monitoring of aerosols
- (b) Monitoring of impact of BC on snow and
- (c) Estimating magnitude of BC sources using inventory (bottom-up) and inverse modelling (top-down) approaches,
- (d) Modelling BC atmospheric transport and climate impact.

I look forward to the implementation of the plan. I take this opportunity to thank Dr. J. Srinivasan, Indian Institute of Science for his perspective and my colleagues in the MoEF for their contributions for preparation of the programme.

Jairam Ramesh
Minister of State for Environment & Forests
(Independent Charge), Government of India

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The Science Plan of the INCCA Black Carbon Research Initiative, National Carbonaceous Aerosols Programme is based on the contributions of J. Srinivasan (IISc), K Krishnamoorthy (SPL), S.K. Satheesh (IISc), A. Kulkarni (IISc), K.J. Ramesh (MoES) and C. Venkataraman (IITB) at the meetings organized by Ministry of Environment and Forests at New Delhi in August, 2010 and at Indian Institute of Science, Bangalore in October, 2010 to workout the details of the scientific programme. The contributions of the following scientists and experts on the draft plan have been noteworthy: M.L. Arrawatia (DST, Sikkim), Shiv Attri (IMD), M. Bhushan (IITB), M.K. Chaudhari (ARAI), Sunil Dhar (Govt PG College, Dharamsala), S.K. Dash (IITD), C.B.S. Dutt (NRSC), Ashwagosh Ganju (SASE), Amit Garg (IIMA), S. P. Gautam (CPCB), S. Ghosh (IITB), T. Gupta (IITK), G. Habib (IITD), Rajesh Joshi (GBPIHED), UC Kulshresta (JNU), R. Kumar (NEERI), M. Kumari (Dayalbagh Institute), J. C. Kuniyal (BPIHED), T. Mandal (NPL), P.R. Nair (SPL), Manish Naja (AIRES), K. Niranjan (AU), G. Philip (WIHG), S. Pushpavanam (IITM), S. Ramachandran (PRL), M.V. Ramana (IIST), K. Achuta Rao (IITD), C.V. Chalapati Rao (NEERI), P.S.P. Rao (IITM), P.D. Safai (IITM), M.M. Sarin (PRL), B. Sengupta (Ex-CPCB), V. Sethi (IITB), Chhemendra Sharma (NPL), Mukesh Sharma (IITK), O.P. Sharma (IITD), R. Sunderraman (IISER), S. Verma (IIT-KGP), Subodh Sharma (MoEF), Rita Chauhan (Natcom Cell, MoEF), Sudatta Ray (Ozone Cell, MoEF). Comments and suggestions by the Ministry of Earth Sciences, Ministry of Science & Technology and Indian Space Research Organization were very valuable.

I

The Indian Network for Climate Change Assessment

The knowledge and understanding of implications of climate change at the national level is inadequate and fragmentary. The Minister for Environment and Forests on October 14, 2009 announced the launch of the Indian Network for Climate Change Assessment (INCCA), which has been conceptualized as a Network-based Scientific Programme designed to:

- ❖ Assess the drivers and implications of climate change through scientific research.
- ❖ Prepare climate change assessments once every two years (GHG estimations and impacts of climate change, associated vulnerabilities and adaptation).
- ❖ Develop decision support systems.
- ❖ Build capacity towards management of climate change related risks and opportunities.

It is visualized as a mechanism to create new institutions and engage existing knowledge institutions already working with the Ministry of Environment and Forests as well as other agencies (MoEF, 2009). Currently, the institutions of the various Ministries such as that of Ministry of Environment & Forests, Ministry of Earth Sciences, Ministry of Agriculture, Ministry of Science & Technology, Defence Research and Development Organisation etc., along with the research institutions of the Indian Space Research Organisation, Council of Scientific and Industrial Research, Indian Council of Agriculture Research, Department of Science & Technology, Indian Council of Medical Research, Indian Institute of Technology, Indian Institute of Management and prominent State and Central Universities, and reputed Non-Governmental Organisations and Industry Associations are working in the various studies on climate change. The scope of the programmes under INCCA has been developed on the basis of the fundamental questions that we ask ourselves for climate proofing systems and the society dependent on climate

and include, inter alia:

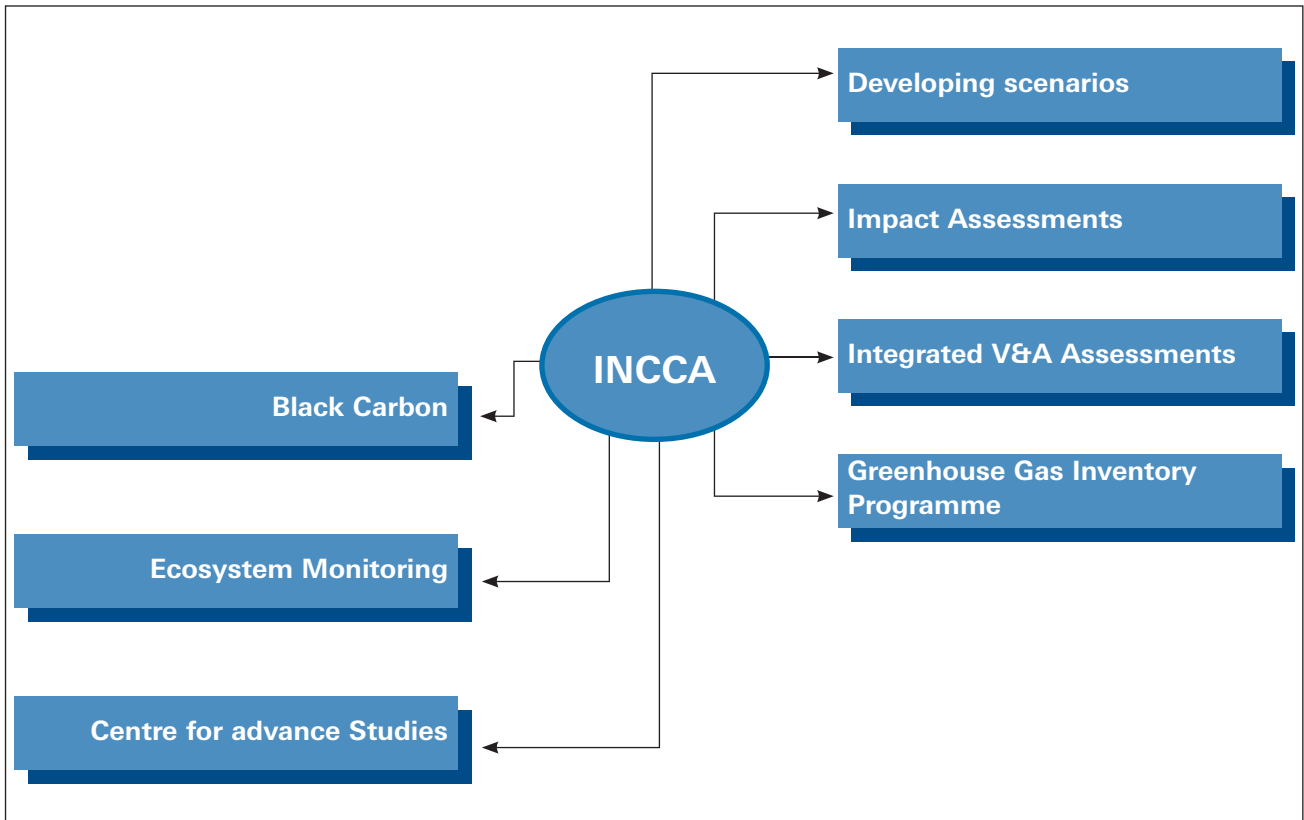
- ❖ Short, medium and long-term projections of climate changes over India at sub-regional scales.
- ❖ The impacts of changes in climate on key sectors of economy important at various regional scales.
- ❖ The anthropogenic drivers of climate change i.e. greenhouse gas and pollutants emitted from various sectors of the economy.
- ❖ The processes through which GHGs and pollutants interact with the climate system and change the biophysical environment.

Climate change may alter the distribution and quality of India's natural resources and adversely affect the livelihoods of its people. With an economy closely tied to its natural resources such as agriculture, water, and forestry, India may face major threat because of the projected changes in climate (NAPCC, 2008).

The mandate of INCCA will continue to evolve to include the new science questions that confront humanity including the population living within the Indian region. The aim of scientific research under INCCA is envisaged to encompass research that will develop understanding on the regional patterns of climate across India, how it is changing over time and likely to behave in the future. Consequently, INCCA will also focus on the impacts of the changing climate on regional ecosystem hotspots, human systems and economic sectors. The following programmes are initially contemplated to be carried out under the aegis of INCCA:

- ❖ A provisional assessment of the Green House Gas emission profile of India for 2007 by sources and removal by sinks;
- ❖ An assessment of the impacts of climate change on water resources, agriculture, forests and human health in the Himalayan region, North eastern region, Western ghats and Coastal regions of India;

- ❖ Undertake an assessment of black carbon and its impact on ecosystems;
- ❖ Undertake a long-term ecological, social, and economic monitoring of ecosystems to identify patterns and drivers of change that influences the sustainability of livelihoods dependent on these systems across India;
- ❖ Build capacity through thematic workshops and training programmes; and
- ❖ Synthesize information thus generated in appropriate communication packages for informed decision making.



Programmes envisaged under INCCA

II

Introduction

1. Background

Aerosols are suspended particulates in the atmosphere and have implications for climate and health through different mechanisms. Several studies have suggested that aerosols may be mitigating global warming by increasing the planetary albedo, although the sign and magnitude of aerosol effects on climate are still uncertain as outlined in the Intergovernmental Panel on Climate Change (IPCC) reports. Compounding to the complexity of this problem is the interaction of aerosols with clouds. Aerosols change cloud properties, alter precipitation patterns and have serious consequences for altering the hydrological balance of the Earth-atmosphere system. Among the various aerosol types, black carbon (BC) aerosol assumes the most importance due to its high absorption characteristics, which in turn depends on its production mechanism. In addition to exerting its own radiative impact, black carbon aerosol can substantially contaminate other aerosol species, thereby altering the radiative properties of the entire aerosol system and in fact their ability to act as cloud condensation nuclei.

The sources of BC are fossil fuel through burning of diesel and solid coal, indoor burning of biomass fuels for cooking and heating and outdoor burning of crop residues, savannas and forests. The source dependence arises because, in addition to emitting BC, these sources also emit organic carbon (OC) and some of the organics absorb solar radiation and amplify the BC warming while others scatter solar radiation and contribute to surface cooling. We need to understand the relative importance of these three BC sources for surface warming, before undertaking BC mitigation efforts.

There have been several inferences on the climate impact of BC aerosols. Some examples are: Black Carbon contributes to droughts and floods in China (Menon et al., 2002); Soot intensifies flooding and droughts in India (Lau et al., 2006); Soot blocks sunlight and results in reduced crop yields (Chameides et al., 1999) and so on. These results are not validated adequately and hence there are several issues to be considered before reaching conclusions on BC climate impact.

Issue-1: Many of the transport models predictions of aerosol characteristics, in general, and BC aerosols in particular, over India are unrealistic.

Issue-2: Many models still assume BC as independent aerosol species (externally mixed).

Issue -3: Several models use unrealistic values of OC/BC ratios for Indian region.

Regional scale chemical transport models and general circulation models typically under-predict aerosol surface concentrations in near source regions (e.g. TRACE-P / INTEX-B, Reddy et al., 2004), including those of BC, because of mixing into grid cells does not represent measurements at a single site. However, these have been largely addressed, by running models at high resolution (e.g. grid of 30 km x 30 km) and through assimilation of observational datasets from satellites, which has permitted models to satisfactorily reproduce regional scale measurements of aerosol and species concentrations in near-source regions (e.g. Carmichael 2009). General circulation models are extensively validated using aerosol columnar properties, which are critical to the prediction of climate variables.

There have been several recent investigations, which revealed that deposition of aerosol black carbon on snow can reduce the snow albedo, leading to enhanced absorption of solar radiation and hence faster melting rates of glaciers. Several investigators on the other hand believe that enhanced warming due to aerosol black carbon at higher levels is responsible for the faster melting of glaciers. Evidence on the record of black carbon deposition in the Himalayan region is only beginning to emerge (Ming et al., 2008), based on ice-core studies. The deposition of absorbing aerosols, including black carbon, 'brown' carbon dust, on the Himalayan ice-pack and glaciers is yet to be understood.

Of late, there is a tendency to project mitigation of BC aerosols as a quick solution to climate change (Jacobson, 2002). However, some studies show that drastic decrease in BC aerosols will result in an increase in surface temperature by several degrees (Novakov et al., 2000). Thus, removal of BC will lead to sudden change in warming/cooling patterns. Consequences associated with such a reduction in BC

should be assessed accurately and adequately before it is implemented to mitigate climate change. Moreover, BC mitigation would not be a solution for the GHG warming.

Given this background, it is imperative that measurements of aerosols, with emphasis on black carbon, from ground, aircraft and space are performed carefully to answer crucial questions related to climate change. These measurements are valuable inputs to climate models for impact assessment. A national effort is essential to address the issue of BC impact on climate. Such a national effort should focus on aspects including, but not limited to, the following (a) Long-term monitoring of aerosols (b) Monitoring of impact of BC on snow and (c) Estimating magnitude of BC sources using inventory (bottom-up) and inverse modeling (top-down) approaches, (d) Modeling BC atmospheric transport and climate impact.

In the following sections, we present the current status and future needs in these aspects.

To understand the impact of dust and black carbon on glaciers we need to understand influence of mineral dust and black carbon on Himalayan seasonal snow cover and glacier. We need to model effect of mineral and carbon dust on snow/glacier albedo, snow melt, glacier mass balance, glacier retreat and snow/glacier melt runoff. Atmospheric aerosol samples will be collected near glaciated valleys and also around seasonal snowfields to understand the proportion of mineral dust and black carbon dust. In addition, samples of seasonal snow, accumulation area and ablation area of glacier to understand the proportion of mineral dust and carbon dust also will be collected. Subsequently, the effect

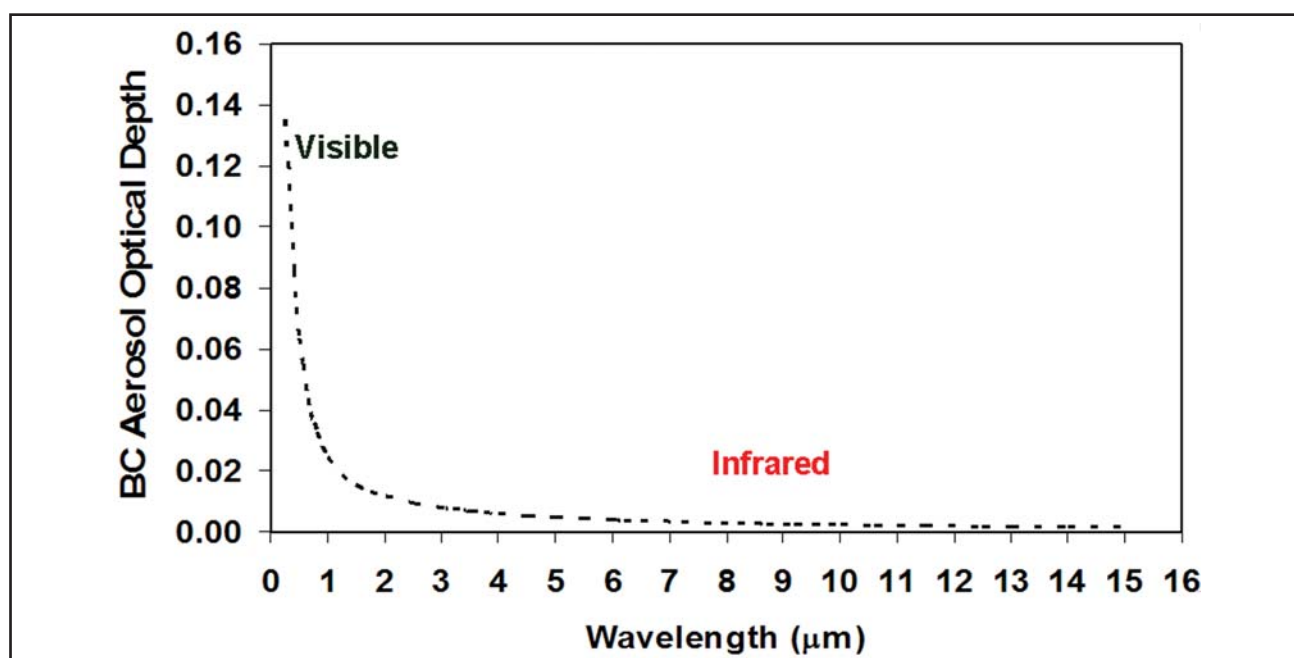
of black carbon and mineral dust on snow and ice albedo will be estimated using field and laboratory observations. An algorithm to monitor snow and glacier albedo using satellite data will be developed and snow/glacier algorithm will be validated

2. Atmospheric aerosols

Direct and indirect climate forcings by aerosols depend on the physical and chemical properties of the composite aerosol, which consist mainly of sulfates, carbonaceous material, sea salt and mineral particles. Among the various aerosol types, black carbon aerosol assumes most importance due to its high absorption characteristics, which in turn depends on its production mechanism. Until the late nineties, sulfate aerosols have received most attention because of its scattering effects and its ability to act as Cloud Condensation Nucleus (CCN). Studies carried out during the late nineties, however, have identified carbonaceous aerosols as one of the most important contributors to aerosol forcing. Carbonaceous aerosols are the result of burning coal, diesel fuels, bio fuels and biomass burning.

3. Black Carbon aerosols

Black carbon (BC) is the result of incomplete combustion of fossil fuels, biofuel, and biomass. It consists of elemental carbon in several forms. Black carbon warms the atmosphere due to its absorption and by reducing albedo when deposited on snow and ice. Life time of black carbon in the atmosphere is only a few days to weeks compared to CO_2 , which has an atmospheric lifetime of more than 100 years.



Spectral variation of BC aerosol optical depth

Even though BC absorbs at all wavelengths, its extinction coefficient is several orders of magnitude smaller (close to zero) at infrared wavelengths compared to visible wavelengths. Therefore, radiative effects of BC are significant at visible wavelengths and not at infrared wavelengths. This is another major difference compared to CO₂. Thus, BC cannot act in a similar way as greenhouse gases.

The largest sources of black carbon are Asia, Latin America, and Africa. Some estimates put that China and India together account for 25-35% of global black carbon emissions. Over the Indian region, however, a decreasing trend in black carbon concentration has been observed.

On a global basis, approximately 20% of black carbon is emitted from burning biofuels, 40% from fossil fuels, and 40% from open biomass burning (Ramanathan and Carmichael, 2008). A more detailed study reports (a) 42% Open biomass burning (forest and savanna burning) (b) 18% Residential biofuel burned with traditional technologies (c) 14% Diesel engines for transportation (d) 10% Diesel engines for industrial use (e) 10% Industrial processes and power generation, usually from smaller boilers and (f) 6% Residential coal burned with traditional technologies.

Black carbon sources vary by region. Some investigators have argued that fossil fuel and biofuel black carbon have significantly greater amounts of black carbon than scattering, making reductions of these sources particularly powerful mitigation strategies. However, this may not hold good for the Indian region because of large Organic Carbon to Black Carbon ratios observed from measurements. Thus, extensive measurements and modeling studies need to be carried out before we can formulate black carbon reduction strategies. Recently, brown carbon (humic like substance) resulting from biomass burning has attracted global attention because of its significantly differing absorption properties, compared to BC. Brown carbon absorbs strongly at blue and UV region, with very little absorption in the mid-visible.

4. Aerosol research in India: Current status

4.1. Measurement of aerosols

It is now well known that aerosols are one of the most important components of the Earth's atmosphere and are of immense scientific interest due to their complex nature and consequent climate effects. Due to their high heterogeneity both spatially and temporally, several field campaigns were undertaken at the national level in recent years to improve the understanding of the optical, physical and chemical properties of aerosols and their radiative impacts. The major

goals of these experiments have been the characterization of regional aerosol properties, their controlling processes and estimation of their direct and indirect radiative forcing. In India, a systematic investigation of the physico-chemical properties of aerosols, their temporal heterogeneities, spectral characteristics, size distribution and modulation of their properties by regional mesoscale and synoptic meteorological processes have been carried out extensively since the 1980s at different distinct geographical regions as part of the different national programs such as the I-MAP (Indian Middle Atmosphere Programme), and later under the ISRO-GBP (Indian Space Research Organization's Geosphere Biosphere Programme).

During the I-MAP, a project was initiated to monitor the aerosol characteristics over the Indian region at a few selected locations. This became operational in the late eighties and has been continued after the I-MAP as a part of ACE (Aerosol Climatology and Effects) project of the ISRO-GBP. A national network called the ARFINET, of Multi-Wavelength Radiometers (MWR), Aethalometers (for measuring BC) and radiation instruments was set up under the ARFI (Aerosol Radiative Forcing over India) project of the ISRO-GBP, to facilitate the long-term observations of aerosols over distinct geographical environments and to assess their impacts on regional climate forcing (Moorthy et al., 1999).

In the following section, a brief survey of efforts to characterize aerosols over the Indian region with special emphasis to BC aerosols is provided. The ISRO-GBP annual review meeting in 1998 recognized the importance of BC aerosols on climate system and it was decided to pursue studies of BC in subsequent years (Moorthy et al., 1999). Details of this research activity are also available in 'IGBP in India 2000 - A status report on projects', edited by R.Narasimha et al. (2000) published on behalf of Indian National Science Academy (INSA). Later, Indian Ocean Experiment (INDOEX), an Indo-US project carried out measurements of BC over the Indian Ocean wherein, extensive measurement of BC was carried out over the Indian Ocean. Based on these measurements, Satheesh et al. (1999) developed an aerosol model for tropical Indian Ocean, which demonstrated that BC contributes 11% to composite aerosol optical depth. Later, using several calibrated satellite radiation measurements and five independent surface radiometers Satheesh and Ramanathan (2000) quantified that even though BC contributes 11% to optical depth, its contribution to radiative forcing can be as much as 60%. Over continental India, Babu and Moorthy (2001) reported the anthropogenic impact on aerosol black carbon mass concentration at a tropical coastal station, Trivandrum. This is probably the

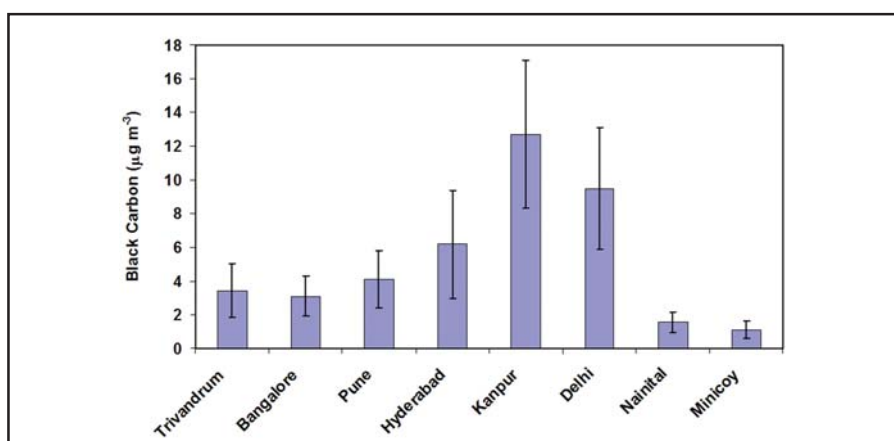
first report of BC over continental India. Thereafter, several investigators reported BC measurements at various locations in India (Babu et al., 2002; Latha and Badarinath, 2003; Babu et al., 2004; Vinoj et al., 2004; Padithurai et al., 2004; Sumanth et al., 2004; Moorthy et al., 2004; Ganguly et al., 2005; Parashar et al., 2005; Dey et al., 2007; Satheesh et al., 2006; Moorthy and Babu, 2006; Pant et al., 2006; Dumka et al., 2006; Ramachandran et al., 2006; Safai et al., 2007; Nair et al., 2007; Sreekanth et al., 2007; Niranjana et al., 2007; Rengarajan et al., 2007; Beegum et al., 2008; Vinoj et al., 2008; Satheesh et al., 2008; Ram et al., 2008; Rastogi and Sarin, 2009; Kumar et al., 2010; Vinoj et al., 2010).

A Road/Land Campaign (LC-I) was conducted during February to March 2004 under the support of the ISRO-GBP, to understand the spatial distribution of aerosol and trace gases over central/peninsular India. Simultaneous measurements were made over spatially separated locations, using identical instruments. These measurements covered an area of more than a million square kilometers over the course of a month from land-based mobile laboratories, and generated a wealth of information on black carbon as well as important aerosol parameters including size, mass concentration, optical depth, and scattering and absorption coefficients using state-of-the-art instruments. The details of these campaigns and the major findings have been reported in literature (Moorthy et al., 2004, 2005; Ganguly et al., 2005; Singh et al., 2006). Based on aircraft-based measurements over Hyderabad, Moorthy et al., (2004) showed a rapid decrease in aerosol black carbon (BC) concentration within the atmospheric boundary layer upto about 500 m.

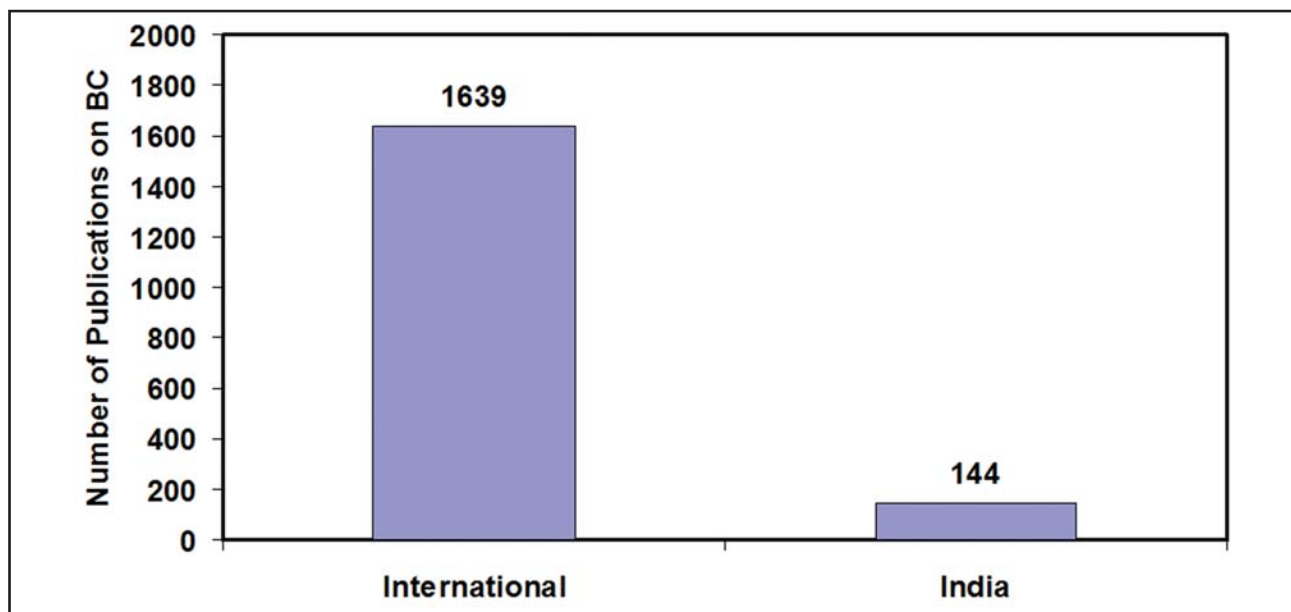
As a continuation of this experiment, Land Campaign-II (LC-II) was organized by the Indian Space Research Organization under ISRO-GBP during December 2004, to characterize the regional aerosol properties and trace gases across the entire Indo- Gangetic belt. The campaign provided a comprehensive database on the optical, microphysical and chemical properties of aerosols over the Indo-Gangetic belt

(Dumka et al., 2006; Tare et al., 2006; Ganguly et al., 2006; Pant et al., 2006; Ramachandran et al., 2006; Srivastava et al., 2006; Niranjana et al., 2006, 2007; Nair et al., 2007; Rengarajan et al., 2007). All these studies showed the persistence of high aerosol optical depth and black carbon concentrations near the surface.

The Integrated Campaign for Aerosols, gases and Radiation Budget (ICARB) was a multi-institutional, multi-instrumental, multi-platform field campaign, where integrated observation and measurements of aerosols with special emphasis on BC, radiation and trace gases along with other complementary measurements on boundary layers and meteorological parameters were made simultaneously. The main goal of the ICARB was to assess the regional radiative impact of aerosols and trace gases, and to quantify the effect of the long-range transport of aerosols and trace gases, involving the Indian mainland, the Arabian Sea, the Bay of Bengal, and tropical Indian Ocean during February-May period of 2006. The ICARB was conceived as an integrated campaign, comprising three segments namely the land, ocean, and aircraft segments. In each one of these segments, collocated measurements of the optical, physical and chemical properties of atmospheric aerosols were carried out. The land segment comprised a network of ground-based observatories, representing distinct geographical features of India, and providing a time-series observation during the period when spatially resolved measurements were made using the moving platforms in the other two segments. As part of ICARB, Satheesh et al., (2008) used wide-ranging multi-platform data from a major field campaign conducted over the Indian region to estimate the energy absorbed in ten layers of the atmosphere. They found that during the pre-monsoon season, most of the Indian region is characterized by elevated aerosol layers. Three-fold increase in aerosol extinction coefficient was reported at higher atmospheric layers (>2 km) compared to that near the surface and a substantial fraction (as much as 50 to 70%) of aerosol



Mass concentration of BC over different locations over India



Number of peer reviewed publications on BC by all scientists across the world and by Indian scientists

optical depth was found contributed by aerosols above clouds. Quantitative estimates of the vertical structure and the spatial gradients of aerosol extinction coefficients have been made from airborne lidar measurements across the coastline into offshore oceanic regions along the east and west coasts of India (Satheesh et al., 2009). The details of these campaigns and the major findings have been reported in literature (Moorthy et al., 2008; Satheesh et al., 2008; Babu et al., 2008; Vinoj et al., 2008; Beegum et al., 2008; Nair et al., 2007; Satheesh et al., 2009, 2010). The BC mass concentration over various locations in India.

Even though all these international and national field experiments and campaigns provide vital information on the optical, physical as well as chemical properties of aerosols, they are limited to a certain period or location due to their specific goals. In this perspective, the long-term experiments at different locations have the added advantages of understanding aerosol influences on a longer time scale, thereby helping us to infer the signs of anthropogenic impact. A sufficiently long time series can also help in inferring climate change signals.

The first report of BC aerosol was published in the former USSR in 1967 (in Colloid Journal) and thereafter there have been 1639 peer reviewed publications so far, of which 144 are published by authors from India.

4.2. Role of Black Carbon on Snow

Today there are about 30 million cubic km of ice on our planet that cover almost 10 percent of the world's land area. In addition, during the northern hemispherical winter, snow

covers almost 66 per cent of land cover. In the Himalayas, the glaciers cover approximately 33, 000 sq. km. area and this is one of the largest concentrations of glacier-stored water outside the Polar Regions. Melt water from these glaciers forms an important source of run-off into the North Indian rivers during the critical summer months. However, this source of water is not permanent as geological history of the earth indicates that glacial dimensions are constantly changing with changing climate. During the Pleistocene, the earth's surface has experienced repeated glaciation over a large landmass. The maximum area during the peak of glaciation was 46 million sq. km. This is three times more than the present ice cover of the earth. Available data indicates that during the Pleistocene, the earth has experienced four or five glaciation periods separated by interglacial periods. During an interglacial period, climate was warmer and deglaciation occurred on a large scale. This suggests that glaciers are constantly changing with time and these changes can profoundly affect the run-off of Himalayan rivers. This change in glaciers can be further accelerated due to green house effect and due to man-made changes in the earth's environment. In addition, large areas of the Himalaya are covered by seasonal snow cover during winter and snowmelt is important during summer time to sustain availability of water in the Indian river systems originating from the higher reaches of the Himalaya. The seasonal snowmelt water is generally available during crucial summer months, when supply of water from rain and glacier is not available. This makes contribution of snowmelt crucial for managing Himalayan water resources.

The Himalayan region can experience warming trends due to additional absorption of solar radiations due to aerosols (termed as 'brown clouds' by some sections of scientists) and also influence albedo of snow and glaciers due to deposition of light-absorbing aerosols on snow and glaciers. This can influence pattern and availability of seasonal snow and glacier melt. Atmospheric brown clouds are generally formed due to biomass burning and also due to fossil fuel consumption. They consist of a mixture of absorbing and scattering aerosols, leading to atmospheric heating and surface cooling. However, some models suggest that over snow/ice surface, where albedo is close to 1, the cooling to negligible and warming effect of absorbing aerosol is largest. In addition, three-fold increase in aerosol optical depth was observed from 1985 to 2000 (Satheesh et al., 2002). This can cause warming in higher altitudes, influencing glacier melt. In addition, if aerosols are deposited on the snow/glacier cover, then it can influence albedo. Small amount of BC aerosols from 120 to 280 ppbw can reduce snow albedo by 4 to 8 percent in visible region. This combination of rise in temperature and reduction in albedo will have significant influence on snow and glacier melt.

Here we discuss a few studies on the effect of aerosols on snow. Xu et al., (2009) have made measurements of elemental carbon and organic carbon from a very high resolution snow core retrieved from a glacier on the south-eastern Tibetan Plateau. They reveal increasing concentrations associated with deposition of anthropogenic aerosols during the period 1998-2005. They reported that elemental carbon and organic carbon concentrations in the core were 4.7 and 56.0 ng g⁻¹ in 1998, but increased to 16.8 and 144.4, and 162.1 ng g⁻¹ in 2005, respectively. Ming et al., (2009) measured the black carbon concentrations in the snow collected from some selected glaciers in west China during 2004-2006. Higher concentrations of BC appeared at lower sites, possibly due to the topography (e.g. altitude) effect. BC concentrations in the snow of Tianshan Mountains outside the Tibetan Plateau (TP) were generally higher than those inside the TP, and strong melting in spring added on more regional/local emissions from the inner TP might both contribute higher concentrations for the central TP than those on the margin of the TP. An estimate of the reduced albedos (over 5%) in some glaciers, which were strongly contaminated by BC in their surfaces, suggested BC deposited in the surface might accelerate the melt of these glaciers in west China.

A continuous measurement for black carbon in a 40 m shallow ice core retrieved from the East Rongbuk Glacier in the northeast saddle of Mt. Everest was made by Ming et al. (2008). This provided the first historical record of

BC deposition during the past similar to 50 yrs in the high Himalayas. This study shows an apparent increasing trend of BC concentrations since the mid-1990s. Seasonal variability of BC concentrations in the ice core indicated higher concentrations in monsoon seasons than those in non-monsoon seasons. Backward air trajectory analysis by the HYSPLIT model indicated that South Asia's BC emissions had significant impacts on the BC deposition in the Mt. Everest region. The estimated average atmospheric BC concentration in the region was about 80 ng m⁻³ during 1951-2001. It was suggested that BC emitted from South Asia could penetrate into the Tibetan Plateau by climbing over the elevated Himalayas. A significant increasing trend of the black carbon radiative forcing since 1990, which even exceeded 4.5 W m⁻² in the summer of 2001. It was suggested that these amplitudes of BC concentrations in the atmosphere over the Himalayas and consequently in the ice in the glaciers could not be neglected when assessing the dual warming effects on glacier melting in the Himalayas. Kim et al., (2005) investigated the role of BC in the Arctic as an agent of climate warming through forcing/feedback of sea ice/glacier albedo. Results suggest that BC aerosols are quickly transported from central Alaska to the Arctic Ocean region of multi-year sea ice and to southern Alaska glaciers, where up to 20% can be deposited. They hypothesized that northern boreal wildfires are a possible contributor in the reduction of first/multi-year sea ice/glacier extent by enhancing summer melting from albedo reduction. Ramanathan et al. (2007) used three lightweight unmanned aerial vehicles that were vertically stacked between 0.5 and 3 km over the polluted Indian Ocean to study vertical distribution of aerosol absorption. They reported that atmospheric aerosols enhanced lower atmospheric solar heating by about 50 per cent. General circulation model simulations, which take into account the recently observed widespread occurrence of vertically extended aerosols over the Indian Ocean and Asia, suggest that aerosols contribute as much as the recent increase in anthropogenic greenhouse gases to regional lower atmospheric warming trends. They proposed that the combined warming trend of 0.25 K per decade may be sufficient to account for the observed retreat of the Himalayan glaciers.

Kulkarni et al. (2007) have investigated Himalayan glacial retreat using data from satellite sensors (with a spatial resolution of 5.8 meters) onboard the Indian Remote Sensing (IRS) satellites. These studies have shown a reduction of 21% in glacier area from 1962 to 2001. Using data from a network of sun photometers over several locations in India, Satheesh et al. (2002) have shown a three-fold increase in aerosol optical depth from 1985 to 2000 over the Indian

region. Satheesh et al. (2008) using aircraft measurements estimates that over central India, more than 70% of aerosol extinction is contributed by aerosols above cloud base. When we examine these two observations in conjunction with the alarming warming rates at higher atmospheric levels (~2 km) and its strong meridional dependence (increasing towards central and north India) reported in Satheesh et al. (2008), it emerges that the large elevated warming by absorbing aerosols above (reflecting) clouds contribute to Himalayan glacial retreat, the response time of which is unknown.

The IPCC also estimated the globally averaged snow albedo effect of black carbon at $+0.1 \pm 0.1 \text{ W/m}^2$.

However, in the Himalaya, systematic investigations to understand influence of aerosols on snow/glacier albedo are not available. Therefore, in this investigation, influence of aerosols on snow/glacier albedo and then effect of change in albedo on snow/ glacier melt will be studied. This programme will be undertaken in collaboration with numerous academic and other agencies.

4.3. Modelling of BC emission inventory and BC climate impacts

The study would have a broader holistic perspective to integrate scientific observations, national circumstances such as socio-economic conditions, technology strategy, and energy security. For instance, non-availability and non-affordability of modern energy choices to the vast Indian rural population and economically backward sections of the society determines use of solid fuels in households and also for heating needs during intense winter in many parts of India. These socio-economic dynamics, technology transitions, economic developments would require intensive treatment since they would drive the activity data for aerosol emissions. Emission inventories or tabulations of emission magnitudes (with appropriate temporal and spatial resolution) are required inputs for atmospheric models and for the development of air quality and climate policies. The accurate assignment of emissions to sectors (e.g. thermal power, diesel transport, residential, agricultural residue burning) is also needed for linking sources to atmospheric abundances and to guide mitigation strategy. Carbonaceous aerosol emissions arise from energy use (including high and low-sulfur diesel fuelled vehicles, residential heating and cooking using coal, wood and other biofuels, small industry, power plants, shipping and oil flares) and the burning of forest, grasslands and agricultural residues (Reddy and Venkataraman, 2002a,b; Garg and Shukla, 2002; Venkataraman et al., 2005; 2006; Bond et al., 2004; Sahu et al., 2008; Ohara et al., 2007; Garg et al. 2006a). In

addition, aerosols form as a result of atmospheric reactions of gases including sulfur dioxide, ammonia, nitrogen oxides and hydrocarbons (Olivier et al. 2001a, ALGAS India 1998, Garg et al., 2006b). A tier-based system of level of detail is adopted for international GHG inventory reporting (IPCC, 2007). Requirements at the highest level of detail (Tier III) include reported fuel consumption for individual large point sources (e.g. power, steel or cement plants), a full definition of technology divisions in use in each sector and measured emission factors representative of technology divisions, fuel composition and operating conditions. In Indian inventories, the level of detail currently available, in activity data and measurements of emission factors under actual field operation, is presently estimated to be medium (Tier II) in industrial sectors and low (Tier I) in rural sectors. This leads to large uncertainties in both magnitude of emissions



and their correct attribution to sectors and sources. In addition, there is a need to harmonize the level of detail in inventories estimating long-lived and short-lived climate agents, to enable an accurate understanding of their relative magnitudes and effects.

Deducing the influence of a multitude of emission sources on atmospheric carbonaceous aerosols needs the integration of measurements with multiple modeling approaches. Methods that use atmospheric aerosol composition to deduce the influence of emission source types on measured aerosol concentration are generally known as 'receptor modeling'. These methods include examining ratios of target chemical compounds including isotope ratios (Gustafsson et al., 2009), measured in time-averaged aerosol samples or in single particles (Guazotti et al., 2003). Among receptor models, the chemical mass balance model (Friedlander, 1973) and positive matrix factorization (Paatero, 1997) have seen wide application in air quality assessment. These models typically exploit detailed aerosol chemical composition data (~15-25 species), sometimes including organic molecular markers

(Schauer et al., 1999). Receptor modeling may also exploit ensembles of trajectories (Ashbaugh et al., 1985) to identify probable source regions affecting concentrations of resolved 'factors'. The outcome is the identification of the pollution source types and estimates of the contribution of each source type to the observed concentrations. Recently, factor analytic inverse modeling approaches to exploit smaller observational datasets, have begun to reveal 'factors' or 'source types,' influencing the abundances of aerosols in different Indian sub-continental regions (Bhanuprasad et al., 2008; Mehta et al., 2009; Cherian et al., 2010). These have been linked to magnitude of emissions from probable source regions, using a combination of trajectory modeling and emission inventory calculations (Garg et al., 2006b; Mehta et al., 2009; Cherian et al., 2010). Recent studies have also examined sources influencing aerosols at urban sites (Baxla et al., 2009; Roy et al., 2009; Chakraborty and Gupta, 2010; SunderRaman et al., 2010a, 2010b; Habib et al., 2010).

Source apportionment methods have been applied to available urban and regional campaign data. However, aerosol measurements from a nationwide network representing a regional background aerosols are more appropriate inputs for such modeling approaches. It would therefore be useful to apply such modeling methods to longer-term observations (one year or multi-year) from several observatories, proposed under this programme, to develop an understanding of carbonaceous aerosol sources on sub-continental scales. In addition to receptor models based on mass conservation, other matrix decomposition methods and Bayesian approaches, offer the opportunity to exploit data of different kinds in a combined manner (e.g. chemical, optical, meteorological), to identify factors, which contain information on both source chemical composition and atmospheric processes.

Atmospheric concentrations of aerosols are predicted in 3-D space and time, by Eulerian forward models including General Circulation Models (GCMs) and regional Chemical Transport Models (CTMs), which need both emissions and meteorology inputs. Globally, GCMs tend to predict lower black carbon (BC) column-integrated concentrations, especially in biomass burning regions (Kinne et al., 2006). Koch et al. (2009) evaluated several global models, described by Schulz et al. (2006), through comparison of predictions with observations. Median model predictions compared reasonably well with measured surface BC concentrations in the United States, were somewhat higher than measurements in Europe, but significantly lower than measurements in Asia. Modeling studies over the Indian region (Reddy et al., 2004; Verma et al., 2006, 2007a, 2008)

showed factors of 3-5 underprediction of carbonaceous aerosol surface concentrations, but more recent studies (Cherian et al., 2010), show better agreement, within factors of 1.5-2. These studies showed better agreement between predicted Aerosol Optical Depth (AOD), and spatially resolved, satellite detected AOD, indicating more satisfactory model simulation of the aerosol column than aerosol surface concentrations. It may be noted that GCMs generally have a coarse spatial resolution (80 to 180 km sized grids in these studies), which may not be representative of measurements at sites affected by micro-meteorological conditions. Model predictions are affected both by emissions and model processes or atmospheric sinks for aerosols. Therefore, multiple models need to be evaluated using the same emissions inputs to understand model uncertainty in predicting aerosol concentrations at the surface and in the atmospheric column.

The net impact of a suite of pollutants emitted by different sectors (e.g. thermal power, diesel transport, industries) has been examined in recent work (e.g. Koch et al., 2007; Fuglestvedt et al., 2008; Shindell et al., 2008; Unger et al., 2010). It has been recently pointed out that calculation of radiative forcing of one compound is often not as useful as the radiative forcing of a complete suite of pollutants emitted by a given emission sector (Unger et al., 2010). In general, reductions of carbonaceous aerosols from combustion sources are accompanied by reductions of NO_x, CO and NMVOCs, providing a link to air quality, including ozone concentrations. Such calculations of multiple pollutants need the use of regional Chemical Transport Models (CTMs), which include modules of gas-phase atmospheric chemistry. The finer spatial resolution of CTMs, from ~5-60 km, allow for more realistic comparison of model predictions with in-situ observations. Chemical Transport Models, such as the STEM model, with a grid resolution of about 60 km, have been used for simulations over south Asia (Adhikary et al., 2008; Carmichael et al., 2009), in a data-guided mode through offline assimilation of satellite products, to obtain good agreement with surface and column aerosol concentrations. A framework of science in support of policy would need regional Chemical Transport Models incorporating reference emissions, emissions for future and mitigation scenarios, to estimate climate impact (say radiative forcing), of selected pollutants, on a regional basis.

Earth's climate response to perturbations by atmospheric constituents, important on regional scales, is not yet fully understood. The climate effects of aerosols are understood through General Circulation Model (GCM) simulations (e.g. Ramanathan and Carmichael, 2008; Chung et al.,



2010) predicting radiative forcing, atmospheric and surface temperatures and precipitation. The ability of GCMs to accurately predict climate effects of short-lived agents like aerosols is influenced by: (i) simplified approximations of various phenomena, (ii) computational/numerical schemes used to solve the resulting complex systems, (iii) ability to mitigate the effect of unknown/poorly-known inputs or parameters by efficiently integrating available measurement data. Modeling studies over the Indian region (Reddy et al., 2004; Verma et al., 2006, 2007a, 2008 ; Verma et al. 2007b., Chung et al., 2010; Cherian et al., 2010), point to the large spatial and temporal variations in aerosol radiative forcing. Carbonaceous aerosol radiative forcing has also been derived from measurements (e.g. Ramachandran and Kedia, 2010).

Atmospheric carbonaceous aerosols significantly change the energy balance of Earth's surface and atmosphere, potentially affecting the water cycle and regional rainfall (Ramanathan et al. 2001, 2005; Chung et al. 2005, Menon et al. 2002; Conant et al. 2003). A regional analysis of global modeling results suggests that different aerosol climate feedback mechanisms could be effective over different regions. Ramanathan et al. (2005) showed that the dimming effect at the surface due to the inclusion of aerosol forcing causes a reduction in surface evaporation, a decrease in meridional Sea Surface Temperature (SST) gradient and an increase in atmospheric stability leading to an overall reduction in rainfall over South Asia. In contrast, Lau et al. (2006) and Lau and Kim (2006) surmised that elevated aerosol heating over the Indo-Gangetic plains in the pre-monsoon period, may lead to a strengthening of the Indian monsoon via surface-atmosphere water cycle feedbacks (the so-called 'elevated heat pump' mechanism). Recent studies, based on observations, have pointed out the need for further investigation, especially on the regional and seasonal distribution of aerosol heating, large aerosol gradients as well as the semi-direct effect (Nigam and Bollasina, 2010, Gautam et al., 2009, 2010).

Chung et al. (2002) examined the impact of these aerosols on the circulation, precipitation and surface exchange patterns over the Indian Ocean region during the January–March period using the NCAR CCM3 General Circulation Model. They have suggested that precipitation increases in the near-equatorial Indian Ocean region but decreases over the global tropics from January to March, due to the presence of this aerosol-related radiative heating/cooling. They did not, however, study the impact of the absorbing aerosol on the strength of the subsequent Indian summer monsoon. Menon et al. (2002) have studied the impact of anthropogenic aerosols over the South Asian and East Asian regions on the Indian summer monsoon. They have used, however, a time invariant aerosol radiative forcing, i.e. aerosol radiative forcing is the same during the pre-monsoon, monsoon and post-monsoon seasons. This is an unrealistic assumption, since there is a strong seasonal variation of anthropogenic aerosol (Satheesh and Srinivasan, 2002). Additionally, these simulations were performed with a coarse resolution GCM (the GISS GCM at 4x5 degree horizontal resolution). The impact of non-absorbing aerosols, such as the sulfate aerosols, has been studied by Boucher et al. (1998). They found that the strength of the Indian summer monsoon reduced with the inclusion of sulfate aerosols. They also found that the response to sulfate aerosol forcing was different from that of the 1987/88 ENSO Sea Surface Temperature forcing. Meehl et al. (1996) have also studied the impact of climate change due to an increase in greenhouse gases and aerosols. Chakraborty et al. (2004), using an atmospheric GCM with aerosol forcing obtained from INDOEX (Indian Ocean Experiment) field campaign, have shown that the change in precipitation during monsoon season due to aerosols depend on the cumulus scheme used in the model. Meehl et al. (2008), using a coupled GCM showed that the effect of black carbon is to reduce Indian monsoon precipitation due to decreased meridional surface temperature gradient. Collier and Zhang (2009), using an atmospheric GCM have shown that monsoon precipitation

over central India increases due to black carbon aerosol on account of reduced stability of the atmosphere. All the above studies looked at the change in precipitation and circulation due to local or global aerosol radiative forcing. Aerosols have both local and remote impacts on climate due to the change in the pattern of heating and circulation of the atmosphere (Chou 2005, Wang 2007).

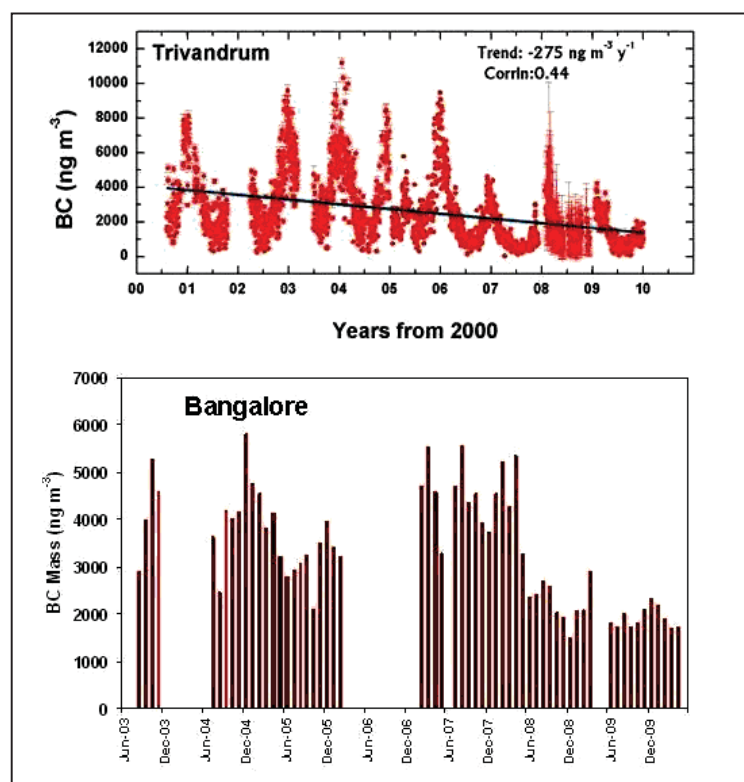
Specifically, the ability of climate models to accurately simulate features of the Indian monsoon, along with its extremes, continues to be in question (e.g. Annamalai, et al., 2007). The inclusion of carbonaceous aerosols is imperative to predict rainfall perturbation on regional scales. The large number of spatially and temporally heterogeneous variables in climate models addressing aerosols, include, but are not limited to, emissions, the mixing state of aerosols, vertical convection and its effect on the vertical structure of aerosols, the response of model predicted relative humidity and rainfall, to differential heating and cooling by aerosols, surface and atmospheric temperature differentials and changes in meridional gradients in the atmospheric and sea-surface temperatures, making this an extremely complex system.

All the studies mentioned above included radiative effects of aerosol on climate. Aerosols also act as Cloud Condensation Nuclei (CCN) to form cloud drops (Twomey, 1959) and have an impact on cloud life-time (Albrecht, 1989). Therefore, aerosols can change the water cycle and climate substantially through modification of clouds. Microphysics of

clouds in Relaxed Arakawa-Schubert (McRAS) convection scheme was introduced by Sud and Walker (1999a, b), and improved later by Sud and Walker (2003, 2004). The McRAS scheme was used in Goddard Earth Observing System (GOES-4) GCM by Sud et al. (2006). This scheme was further modified to include aerosol indirect effect with a new precipitation microphysics by Sud and Lee (2007). Using this scheme in GOES-4 GCM, Krishnamurti et al. (2009) have shown that aerosol plume from over the west coast of India to the Arabian Sea can substantially change the winter precipitation and atmospheric circulation over that region. These aerosol plumes created a local Hadley cell in north-south direction over the Arabian Sea. However, there remain large uncertainties in such formulation of aerosol effect in cloud microphysics due to lack of knowledge of cloud-aerosol interaction. Further detailed modeling studies are required to access the actual effect of aerosols as CCNs on climate.

5. What we know

The ISRO-GBP is maintaining 37 surface observatories covering representative locations in India. All these sites have BC measurements. The duration of data available from these sites varies with location depending on the start date of measurements at each location. In addition, there have been a few field campaigns such as ISRO-GBP's LC-I, LC-II and ICARB. Thus, we have information on the spatial



Trends in BC mass concentration observed over Trivandrum and Bangalore

and seasonal variation of BC at the Earth's surface. ICARB aircraft segment carried out a few measurements of altitude profiles of BC aerosols.

Recently, Ramana et al. (2010) have argued that fossil-fuel-dominated BC plumes are more effective (~100% more efficient) as warming agents compared with BC from biomass burning-dominated plumes. Modeling studies have estimated that the net warming effect of fossil fuel BC is larger than that of biomass fuel cooking (Jacobson, 2004). According to Jacobson (2002), control of BC, "particularly from fossil fuel sources, is very likely to be the fastest method of slowing global warming" in the immediate future. The fossil fuel contribution to the total BC is only about 30% over South Asia and is about 60-80% over East Asia, USA and Europe on the basis of emission inventories. In addition, observation-based atmospheric-aerosol source-apportionment studies also show that biomass fuel BC is the main source in South Asia (Venkataraman et al., 2005; Gustafsson et al., 2009). The largest fossil fuel BC to total BC values now is found in Europe, USA and East Asia. This information is very important as far as BC reduction strategies are concerned.

6. What we don't know

It appears that what we don't know about aerosol BC is much more than what we know. Additional implications of such a study would include multi-dimensional implications of impacts assessment from aerosols, such as on snow-cover, cloud cover and monsoons. Thus measurements may have to be conducted for longer durations for enhancing predictability of results and reducing the uncertainty of inferences drawn.

6.1. Vertical distribution of BC

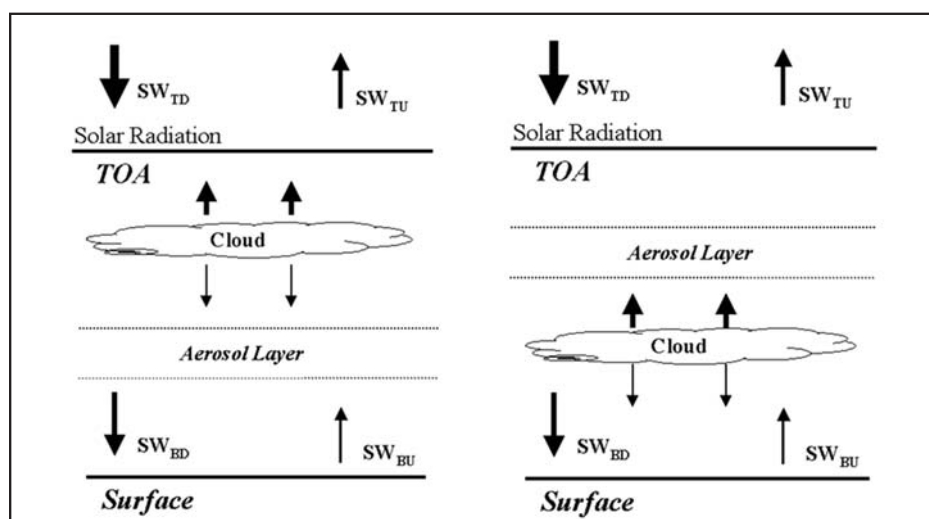
Even though we have a few measurements of vertical profiles of BC using ICARB aircraft experiment, they are mostly limited to coastal and oceanic regions. As of now we don't know vertical distribution of BC aerosols over continental India, except a few isolated measurements. When the amount of absorbing aerosols such as BC, are significant, aerosol optical depth and chemical composition are not the only determinants of aerosol radiative effects, but the altitude of the aerosol layer and its altitude relative to clouds (if present) are also important. Thus, it is essential to gather information on vertical distribution of BC aerosols.

6.2. State of mixing of BC with other aerosols

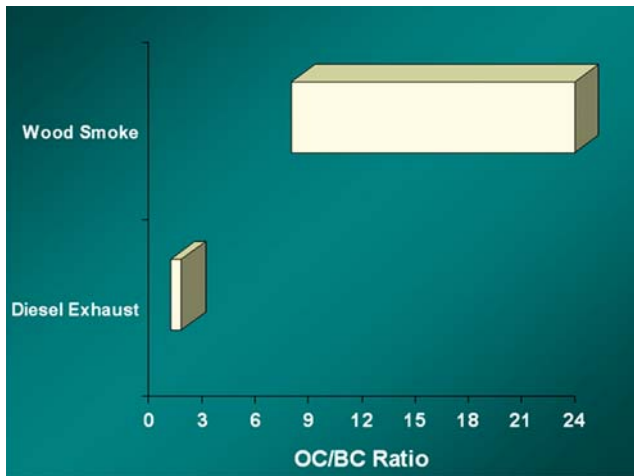
Recent studies have shown that when sulphate or organics is coated over BC aerosols, its absorption effects are enhanced by 50% (Bond et al., 2004). In case of BC mixed with large dust particles, absorption of the composite dust-BC system is enhanced by a factor of two to three compared to sum of BC and dust absorption (Chandra et al., 2004). However, we have no information on the state of mixing of BC.

6.3. Effect of BC on cloud cover

Recent studies have shown that absorbing aerosols such as black carbon or dust absorb incoming solar radiation, perturb the temperature structure of the atmosphere, and influence cloud cover (Ackerman et al., 2000; Koch and Genio, 2010; Leaitch et al., 2010). The effect of BC on cloud cover depends on several factors, including the altitude of the BC relative to the cloud and on the cloud type. It has been shown that cloud cover is decreased if the BC is embedded in the cloud layer (Ackerman et al., 2000). However, reduced cloud cover leads to more solar radiation reaching the surface, which in

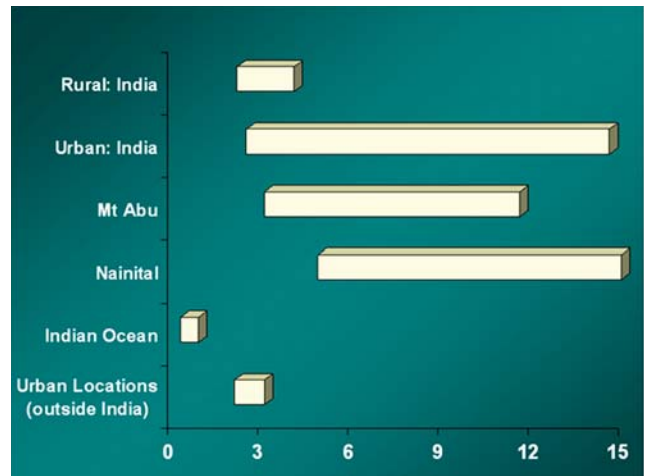


Representation of aerosol layers above and below clouds



(a)

(a) OC/BC ratios for wood smoke and diesel exhaust



(b)

(b) OC/BC ratios observed over various locations in India

turn intensify convection and produce more clouds at some other level. Absorbing aerosols below cloud can enhance convection and hence cloud cover, whereas absorbing aerosols above cloud-level can stabilize the underlying layer and reduce further growth of cumulus clouds (Koch and Genio, 2010). In order to investigate these effects, it is essential to have aircraft-based studies.

6.4. Can mitigation of BC aerosols lead to cooling of the atmosphere?

The question of whether aerosols cool or warm the planet depends on the relative contribution of various chemical species, which constitute the aerosol. An aerosol with significant BC content can have net warming effect and complement the green house warming. Several investigators report that as of today, the heating by black carbon is mostly offset due to cooling by sulphate aerosols. Thus, it appears that net effect is cooling by organic aerosols.

It is known that OC/BC ratio is less than 1.0 in the case of diesel exhaust whereas that from wood smoke is much larger than 1.0 (see Fig. 6). Studies over the Indian region show that OC/BC ratio is in the range from 3 to 15.

If aerosol consists of BC, it can warm the atmosphere due to its shortwave absorption, but simultaneously it cools the Earth's surface by reducing the incoming solar radiation. Atmospheric temperature decrease due to this surface dimming is larger than atmospheric warming by BC. Thus, close to Earth's surface, aerosol actually cools the atmosphere.

While BC is the major aerosol species which absorbs light, scattering due to BC and all other aerosol species leads

to cooling of Earth's surface. Novakov et al. (2008) have shown using data over California that reduction of BC leads to further warming. This aspect needs to be studied before attempting any BC reduction strategies. It is possible that a drastic decrease in BC aerosols may result in an increase in surface temperature by several degrees. Consequences associated with such a reduction in BC should be assessed accurately and adequately before it is implemented to mitigate climate change. Reduction of BC should not be considered as a means or a shortcut for not reducing CO₂ emissions, because this alone is not a universal remedy for global warming, but only a temporary relief, not a cure, which is curbing the GHGs.

6.5. Effect of BC on Monsoon

There have been contrasting inferences on the impact of BC on monsoon. Lau et al. (2006) in 'Climate Dynamics' stated that "Absorption of solar radiation and consequent warming by aerosols over Tibetan Plateau (elevated land) acts like an 'elevated heat pump (EHP)', which draws in warm and moist air over the Indian sub continent leading to advancement and subsequent intensification of Indian summer monsoon".

Ramanathan et al. (2005) stated that "Large reduction of solar radiation at the Earth's surface simultaneous with lower atmospheric warming increases atmospheric stability, slows down hydrological cycle and reduces rainfall during monsoon".

The consequence of these contrasting processes needs to be understood before arriving at conclusions on the aerosol impact on regional climate system.

III

Methodology and Approach

1. Long-Term Monitoring of Aerosols

Major objective is to monitor key aerosol parameters by establishing long-term monitoring stations. Already existing networks such as ARFI network of ISRO will be utilized for this purpose.

1.1. Approach

A hybrid approach, which involves field experiments including network measurements as well as aircraft-based field measurements simultaneous with multi-satellite analysis is essential for the impact assessment of aerosol black carbon over India. Combining measurements with multi-satellite data can create synergy to the benefit of each other. This approach will provide new insights into the problem and new

methodologies to gather information on black carbon aerosol can be formulated. Using the outcome of this project, crucial questions related to climate impact of black carbon aerosols can be addressed.

1.2. Action Plan

Network Measurements: Establishment of a network of aethalometers (which measure black aerosols) over entire the Indian region. Approximately 60 instruments need to be deployed. Each instrument will be automated and transmit data to a common data centre. Measurements will continue for 5 years. Maps of BC as well as its optical properties over entire India can be constructed starting from the third year and can be made available in web on a daily basis.

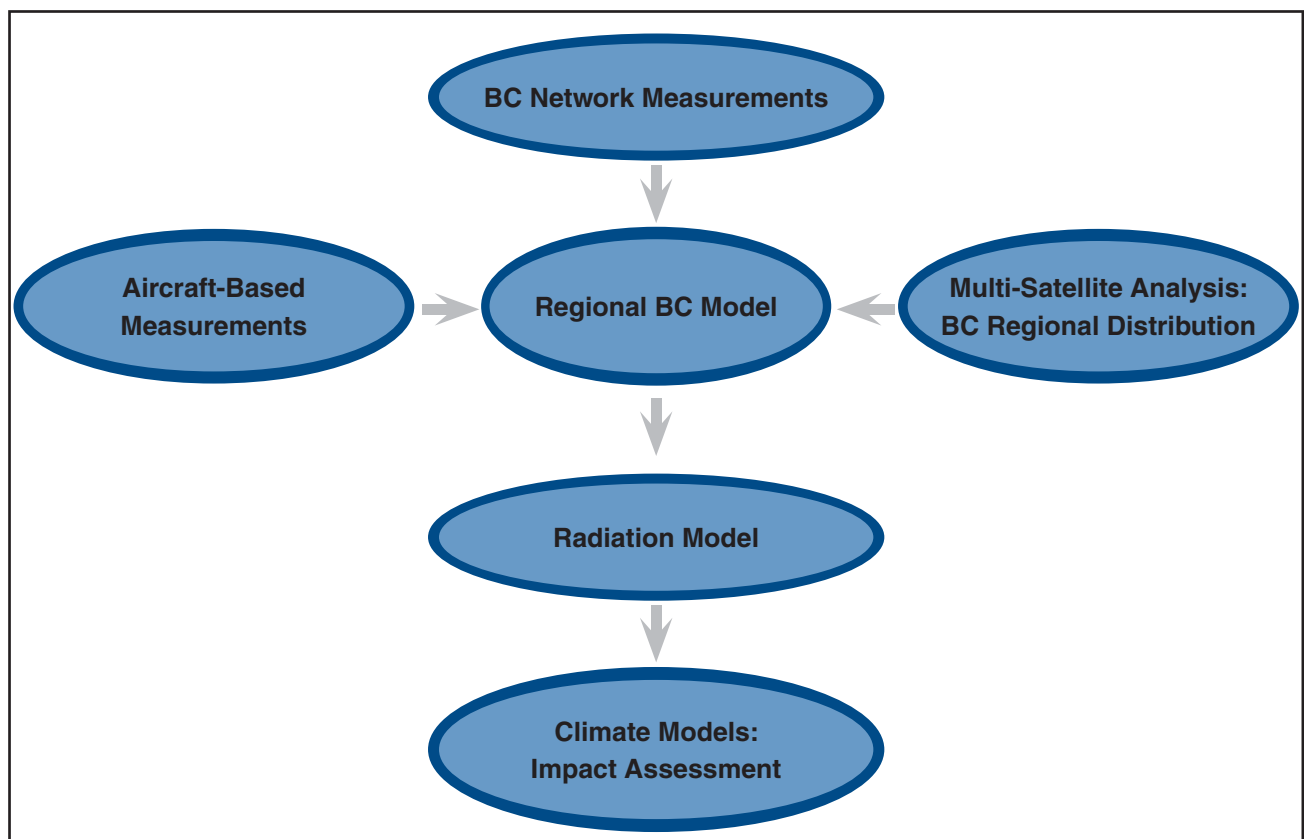
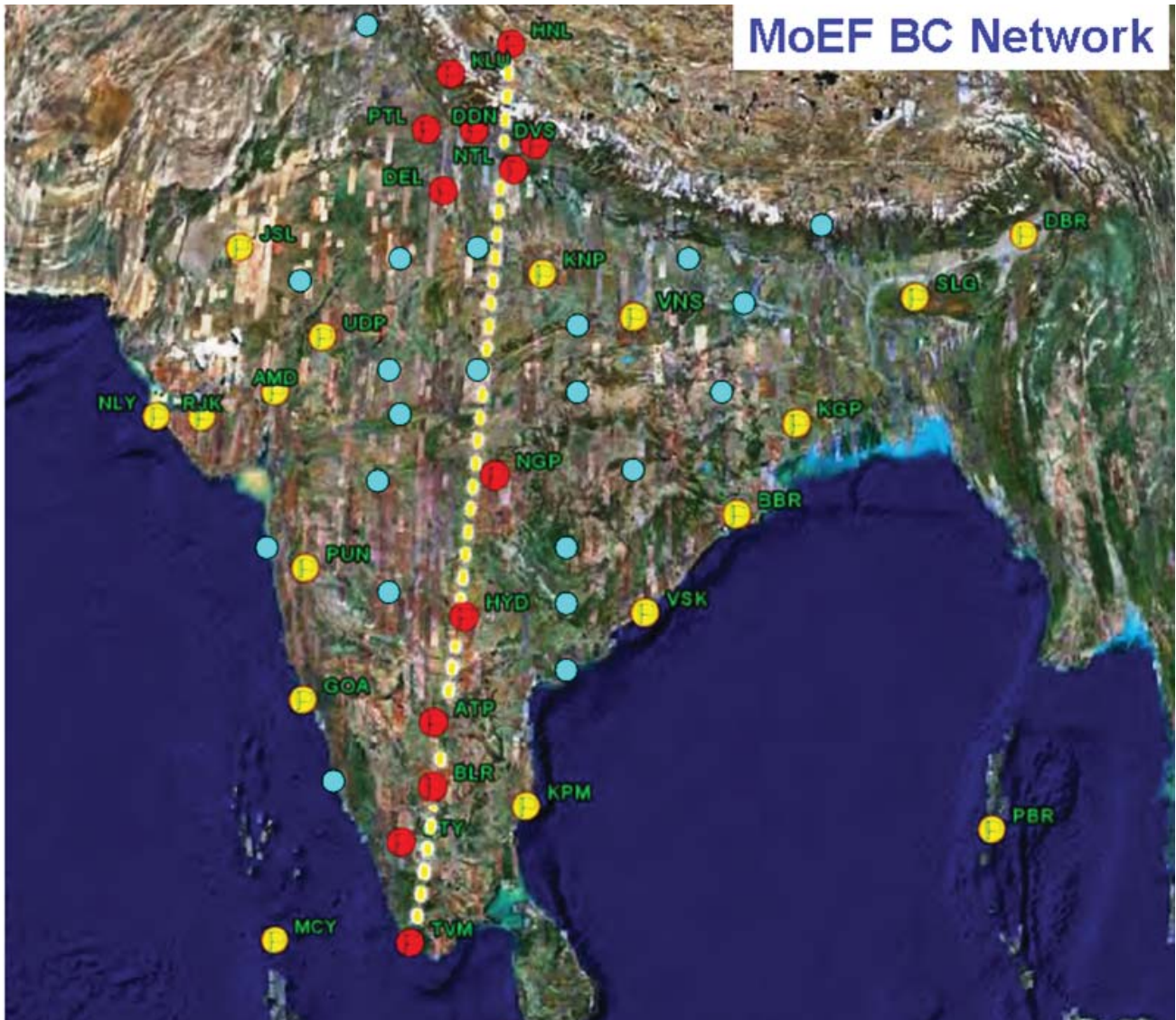


Illustration of the approach: To monitor, analyse and assess the impact of black carbon aerosols.

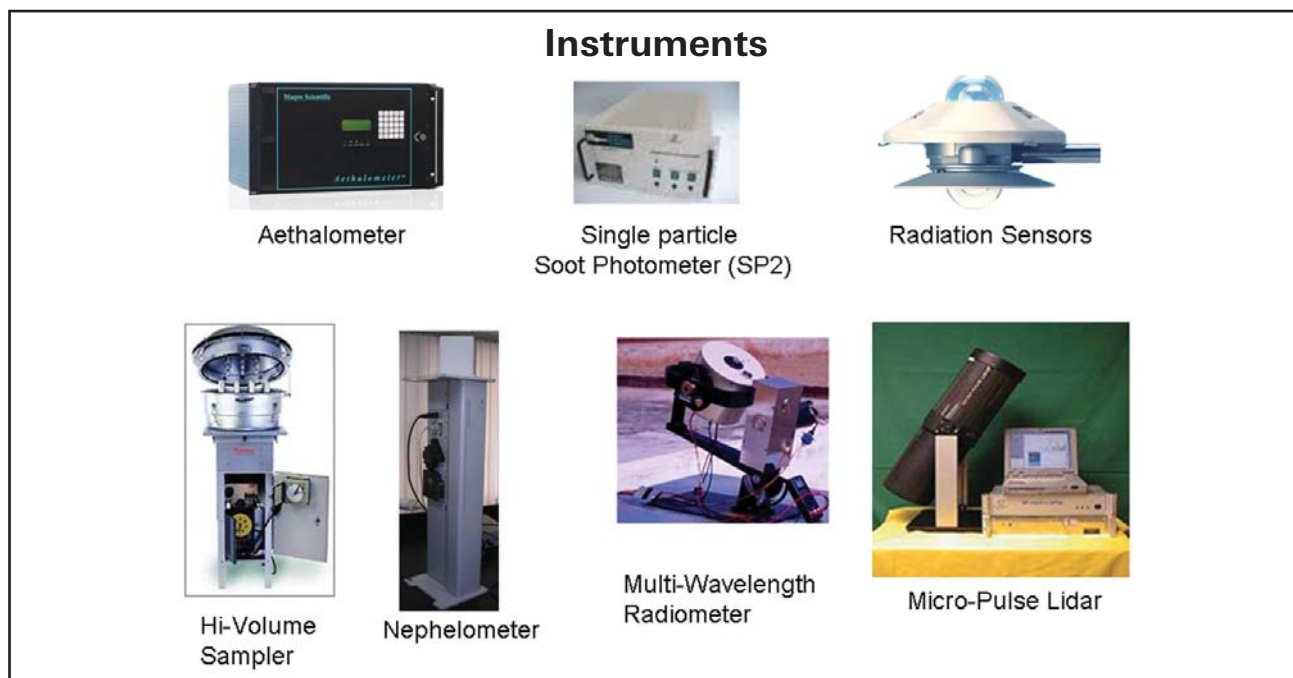


Proposed MoEF network (tentative map) superimposed over the existing ARFI network

In this exercise, the advantage of available BC networks established by other departments such as DOS and MoES will be fully utilized to avoid duplication of efforts and increase the spatial resolution of the network.

The network of sites maintained by ISRO's ARFI programme is shown in the above figure. Additional sites to be set up under the NCAP programme of MoEF are shown as blue filled circles. These sites are listed below:

- | | |
|--|---|
| 1. Jodhpur (Central Arid Zone Research Institute, CAZRI) | 9. Aurangabad (B.R. Ambedkar University) |
| 2. Bhopal (IISER, Bhopal) | 10. Kancheepuram (Hindustan University) |
| 3. Ujjain (Vikram University) | 11. Ranchi (BITS) |
| 4. Indore (IIT, Indore) | 12. Patna (Patna University) |
| 5. Agra (B.R. Ambedkar University) | 13. Darjeeling/Siliguri (University of North Bengal) |
| 6. Allahabad (University of Allahabad; NIT) | 14. Gorakhpur (Deen Dayal Upadhyay Gorakhpur University) |
| 7. Jabalpur (Rani Durgavati Viswavidyalaya,) | 15. Jaipur (BIT Extn. Centre, / Birla Inst. of Sci. Res. (BISR),) |
| 8. Raipur (NIT) | 16. Warangal (NIT) |
| | 17. Solapur (Solapur University) |
| | 18. Vijayawada (NTR University) |
| | 19. Mangalore (University of Mangalore) |
| | 20. Mumbai (IIT) |
| | 21. Machilpatnam (Krishna University) |
| | 22. Shadnagar, Hyderabad |
| | 23. Srinagar (University of Kashmir) |



Instruments used for Measurements

Why Aircraft Measurements?

Based on recent observations using aircraft-based measurements, it has been reported that during pre-monsoon season, most of the Indian region is characterized by elevated aerosol layers (with layer heights at around 2 to 3 km). This means that surface measurements alone are not sufficient, but altitude distribution of black carbon is also essential. It is also important to note that there are indications of strong North-South as well as East-West gradients in black carbon abundance depending on the season.

Multi-wavelength LIDARs: About 20 multi-wavelength LIDARs will be deployed by dividing the entire Indian region into zones based on aerosol sources. Polarized back-scatter signal will be used to obtain BC properties. This is required as aircraft cannot cover the entire region simultaneously.

Mobile Facility: Mobile facility with a suite of instruments is intended to make concurrent measurements of climate sensitive aerosol parameters from distinct environments, hot spots and source regions in a campaign mode.

Multi-Satellite Analysis: It is well known that no single satellite is capable of providing information on aerosol black carbon. Recent studies demonstrated that multi-satellite analysis can provide information on absorbing aerosol species such as black carbon. Combining measurements with multi-satellite data can create synergy to the benefit of each other. While satellite retrievals require validation from air-borne and ground-based measurements, network or air-borne measurements cannot cover the entire region and hence satellite data can fill the gaps.

While the entire BC network will be in place, special focus needs to be given to northern Indian and Himalayan regions as well as north-south chains. International Commission for Snow and Ice (ICSI) stated in their report that “Glaciers in the Himalayas are receding faster than in any other part of the world”. Given the fact that Himalayan glaciers are headwaters of several major rivers in north India, this can pose a major threat to the water supply to a billion people. Thus, it is absolutely essential to investigate the role of black carbon on Himalayan glacier retreat (both as a result of BC deposition on snow as well as warming by elevated BC aerosols).

1.3. Technical Aspects

Filter-Based versus Optical Methods

Filter-based aethalometers are used in ISRO network to measure BC aerosols. Filter-based methods like the Aethalometer detect light transmission through a fibrous filter sample. However, this technique is affected by multiple scattering effects and various corrections have to be made for this scattering artifacts, in order to obtain the particulate light absorption. Further, non-absorbing aerosol can affect the measured light absorption.

A Single-Particle Soot Photometer (known as SP2) detects black carbon in particles by passing them through an intense laser beam. The laser light heats BC in particles causing them to vaporize in the beam. Detection of wavelength-resolved thermal radiation emissions provides quantitative information on the BC mass of individual particles. The SP2

has become increasingly recognized as a tool for quantifying BC aerosol.

The BC measurements as part of ISRO-GBP network were initiated in 2000 and used filter-based measurement techniques such as aethalometer. Use of SP2 for the entire network is envisaged.

2. Impact of Aerosols on Himalayan Glaciers

2.1. Objectives

- ❖ To understand the influence of mineral and black carbon on Himalayan seasonal snow cover and glaciers.
- ❖ To model effect of mineral and carbon dust on snow/ glacier albedo, snow melt, glacier mass balance, glacier retreat and snow/ glacier melt runoff.

2.2. Methodology

- ❖ Collection of atmospheric aerosol samples near glaciated valleys and also around seasonal snow fields to understand the proportion of mineral and carbon dust.
- ❖ Collection of samples of seasonal snow, accumulation area and ablation area of glacier to understand proportion of mineral dust and carbon dust.
- ❖ Estimation of effect of black carbon and mineral dust on snow and ice albedo using field and laboratory observations.
- ❖ Development of algorithm to monitor snow and glacier albedo using satellite data.
- ❖ Validation of snow/ glacier algorithm and monitoring albedo using satellite and aircraft data.
- ❖ Understanding effect of change in albedo due to black carbon on seasonal snow and glacier melt.
- ❖ Estimation of albedo and reflectance of seasonal snow and glacier, glacier depth and mass balance using airborne sensors like laser altimeter, ground penetrating radar and pyronometer.
- ❖ Modeling effect of enhanced melting on glacier mass balance and retreat.
- ❖ Development of snow/ glacier melt runoff models to understand influence of changes in snow and glacier melt pattern.

2.3. Study Area

The study area will be finally selected in consultation with collaborating agencies. However, these will be distributed in different regions of the Indian Himalayas from Jammu and Kashmir to Sikkim. The field investigations will be carried out during winter time to understand influence of BC on seasonal snow melt pattern and summer on accumulation area of the

glaciers. The locations for seasonal snow cover studies will be prepared in consultation with collaborating agencies. The tentative list of glaciers is given below:

3. Modelling of BC emission inventory over India and Assessment of its impacts

Modeling of black carbon emission inventory for India and its climate impacts are focused mainly on the four aspects (a) Development of an Indian emission inventory for carbonaceous aerosols (b) Understanding sources influencing carbonaceous aerosols through inverse modeling approaches (c) Understanding the regional atmospheric abundance of carbonaceous aerosols through chemical transport modeling and (d) Understanding the influence of carbonaceous aerosols on regional climate change and climate futures through general circulation modeling. The objectives and approach corresponding to each of these themes are described below:

3.1. Development of an Indian emission inventory for carbonaceous aerosols

3.1.1. Objectives:

- ❖ Development of a national carbonaceous aerosols emission inventory, with an IPCC Tier II to Tier III level of detail.
- ❖ Evaluation of the impact of sectors and sources on the magnitude of carbonaceous aerosol emissions.
- ❖ Identification of specific source and technology types, which emit highly warming particles (including carbonaceous aerosols and co-emitted species).

Table-1: Tentative list of glaciers

Name	Basin	State
Drung Drung	Indus	Jammu and Kashmir
Rulung	Indus	Jammu and Kashmir
Parkichy	Indus	Jammu and Kashmir
Kolhoi	Indus	Jammu and Kashmir
Patsio	Indus	Himachal Pradesh
Chhota Shigri	Indus	Himachal Pradesh
Parbati	Indus	Himachal Pradesh
Shaune Garang	Indus	Himachal Pradesh
Gangotri	Ganga	Uttarakhand
Dokariani Bamak	Ganga	Uttarakhand
Satopant	Ganga	Uttarakhand
Tipra Bank	Ganga	Uttarakhand
Zemu	Tista	Sikkim
East Rathong	Tista	Sikkim
Lonak	Tista	Sikkim

- ❖ Future emission projections in an integrated economic-energy-environment framework.

3.1.2. Methodology and approach:

- ❖ Identification of carbonaceous aerosols and co-emitted species of relevance to regional air quality and climate (including products of incomplete combustion like N₂O, NO_x, CO, NMVOCs).
- ❖ Identification and enumeration of carbonaceous aerosol emission sectors including, but not limited to, high and low-sulphur diesel fuelled vehicles, residential heating and cooking using coal, wood and other biofuels, small industry, power plants, shipping and oil flares and the burning of forest, grasslands and agricultural residues. Identification of technology divisions and technology types. Identification of level of detail to be followed by all participants for emissions estimation.
- ❖ Obtaining and evaluating activity data through the involvement of appropriate government agencies, research institutions and private sector. These would be in the form of conducting all-India representative surveys for diesel consumed in private generator sets, usage of off-road vehicles, seasonal combustion of traditional biomass, biomass combustion in formal and informal sectors of economy such as hotels and commercial establishments, brick kilns, cement factories, glass manufacturing, ceramics etc, coal combustion in unorganized sectors and households etc. Assessment of existing technologies in large and medium point sources would also be made based on industry and site surveys as aerosol emissions have technology specificity. Involvement of private sector and industry associations would therefore be required for such a large national scientific exercise.
- ❖ Identification of relevant sources and technologies for detailed measurements of on-road and in-field emission factors representative of technology divisions and operating conditions. These would include diesel vehicles of light and heavy duty with specific attention to vehicle age and 'super-emitters', rural and agricultural practices and sources, e.g. wood burning for agricultural processing, commercial food preservation, inorganic fertilizer/pesticide use, agricultural burning, diesel pump sets, residential wood and biofuel burning for cooking and heating.
- ❖ A large measurements effort is needed to measure source profiles for the multitude of carbonaceous aerosol sources, especially those in the rural and informal sectors. A strong measurements component is needed which requires the identification of 'molecular markers' for specific sources of carbonaceous aerosols relevant to the Indian region.
- ❖ Calculation of emission magnitudes and uncertainties at district, state and national levels. Identification of appropriate proxies for gridding at spatial resolution of 5-50 km.
- ❖ Conducting economic-energy-emission modeling at sufficient depth for future energy usage and related aerosol emission projections wherein alternate scenarios may be created to capture future dynamics including socio-economic projections, technology enhancements, and policy interventions. It would also be extended to model Indian urban and rural area dynamics appropriately – either together or separately. Energy availability, affordability and therefore energy choices are different for urban and rural areas and play an important role in determining related aerosol emissions. Economic-energy-emission modeling would also provide analysis of aerosol mitigation options. This would be linked with technology strategies and policy options to reduce aerosol emissions.
- ❖ Development of a GIS or other database system for mining the inventory data and providing for calculations of the impact of interventions and of future emissions. Development of pre-processors needed to provide gridded emissions at different spatial resolution for input to different climate models and / or to aid government decision making.
- ❖ Private accreditation laboratories could also be roped in appropriately for measurement authentication and international benchmarking. This proposal represents a major Indian research effort and scientific inputs from all stakeholders would be welcome, based on their readiness and capabilities to provide the same.

3.2. Understanding sources influencing carbonaceous aerosols through inverse modelling approaches

3.2.1. Objectives

- ❖ Deducing carbonaceous aerosols sources on subcontinental scales, aerosol chemical information and relevant meteorological or aerosol extinction data, through receptor modeling.
- ❖ Furthering an understanding of sources influencing carbonaceous aerosols in different regions and seasons.

3.2.2. Methodology and approach

- ❖ In conjunction with the proposed national network of observatories for carbonaceous aerosol measurement, within programme, appropriate filter-based, low-volume, speciation samplers will be identified and procured, for collection of particle matter smaller than 2.5 µm in diameter (designated PM_{2.5}) on multiple filter substrates.
- ❖ Time averaged aerosol samples will be collected for appropriate durations (24-h at background sites and 1-week at remote sites) on regular intervals (4 to 10 per month for a 1 year sampling period). This may be repeated for a second year as per need.
- ❖ About ten collaborating institutions will be identified to undertake detailed chemical analysis of samples from selected sites (say 30 of the 60 proposed observatories).
- ❖ The chemical species analyzed must include signature compounds for specific regional sources, including, but not limited to inorganic ions (K, Ca, Mg, Na, NH₄, Cl, NO₃, SO₄), trace elements (Si, Al, Cd, V, Se, Pb, S, Ni, Mn, Fe, Co, Ti, Sb and Sn), carbonaceous constituents (OC, EC) and temperature resolved carbon fractions (OC1, OC2, OC3, OC4, OC5, OP, EC1, EC2, EC3) analysis and total mineral matter. The possibility of making carbon isotope measurements on filter-collected particles will be evaluated and appropriate institutions identified to undertake this work.
- ❖ Additional identification of markers (maybe at 1-2 laboratories) could include GC/MS analysis for detailed analysis of organics in filter substrates, IC analysis of low molecular weight water-soluble organic acids and HPLC-fluorescence for a small suite of PAHs (since vehicular traffic would be a major source of carbonaceous aerosol in urban regions). GC-MS can be utilized to identify organic molecular markers for combustion sources like levoglucosan (biomass), hopanes (coal), diacholestane (cowdung).
- ❖ Appropriate analytical instruments needed for chemical analysis will be identified at the programme level. Typically ion chromatograph with conductimetric detector, IC, inductively coupled plasma-atomic emission spectroscope, ICP-AES, and thermal evolution and optical reflectance-based carbon analyzer, TOR, GC-MS, ED-XRF, acquired by the groups for dedicated use for the programme. These groups will also be responsible for receptor modeling using the chemical data.
- ❖ A workshop will be held to develop measurement SOPs, QA/QC protocols and uncertainty reporting common to all participating laboratories, which will be adopted during sampling. Blind samples will be sent for analysis at participating labs at regular intervals.
- ❖ A workshop will be held on receptor modeling - positive matrix factorization and trajectory and wind data-based models such as the potential source contribution function and combined probability function.
- ❖ Groups will perform source apportionment calculations and appropriate diagnostics to report 'factors' or sources identified from the chemical data during different seasons. A synthesis of the identification of carbonaceous aerosol sources on sub-continental scales will be made.
- ❖ Synchronizing scientific measurement of emission levels with estimates of emissions (activity data X emission factors) and results of inverse modeling would also be pursued. This could provide more robustness and convergence to emission estimates.

3.3. Understanding the regional atmospheric abundance of carbonaceous aerosols through chemical transport modelling

3.3.1. Objectives

- ❖ Prediction of carbonaceous aerosol transport, atmospheric concentration and deposition using reference emissions, input to simulations made with selected CTMs for a period of one year.
- ❖ Synthesis and evaluation of carbonaceous aerosol concentration and wavelength-dependent radiation measurements available over India.
- ❖ Evaluation of seasonal and spatial variability of CTM predicted carbonaceous aerosol concentrations with measurements from the observatory network.
- ❖ Identification of the influence of carbonaceous aerosol emission sectors on their seasonal and spatial atmospheric abundance, through source-tagged emissions inputs.
- ❖ Identification of the influence of emission sector and atmospheric processes on the deposition of carbonaceous aerosols on target ecosystems including the Himalaya.
- ❖ Exploring data-guided techniques (like offline interpolation of model outputs to satellite derived aerosol products) for improvement of model predictions.
- ❖ Estimation of radiative forcing, using CTM outputs in

radiation transfer models, with selected aerosol optical properties.

3.3.2. Methodology and approach

- ❖ Identification of about five modeling groups in the country with existing capacity to run CTMs and those with willingness to develop this capacity. Identification of multi-processor machine configurations needed to run CTMs in tracer mode and with full atmospheric chemistry. Procurement of machines and installation at modeling institutes.
- ❖ Identification and deployment of suitable open-source CTMs or those available through collaborations (e.g. the STEM-2K1 model of the U Iowa, the ICTP REMO model, WRF-CHEM from NOAA and others) for atmospheric simulations. Model porting and operationalisation will be needed along with evaluation of model operation against standard runs available with model developer.
- ❖ Evaluation of available carbonaceous aerosol observations over India. Examination of the sensitivity of the chosen model(s) and ability to reproduce measurements on spatial and seasonal scales. Ability of models to reproduce surface to lower troposphere variation in measured carbonaceous aerosol concentrations.
- ❖ Meteorology modeling (say WRF with NCEP re-analysis data) at appropriate spatial resolution (say ~30 km over India, with nesting at ~5 km over sensitive ecosystems) as common input to all CTMs. Pre-processing of WRF output to model-ready data input files.
- ❖ Sensitivity analysis of all models to phenomenological parameters (deposition velocity, SO₂ reaction rates, scavenging ratio, ratio of hydrophobic to hydrophilic fraction) and two versions of emissions, through simulations for 4 months (say Jan, Apr, Jul, Oct), followed by model inter-comparison analysis.
- ❖ Simulations (in tracer mode, without online atmospheric chemistry) for a one year period with reference emissions and evaluation with carbonaceous aerosol measurements from the observatories. Optimal assimilation of satellite data will be done to improve model predictions.
- ❖ In second-phase of programme period, simulations with source-tagged emissions (i.e. with emissions inputs modified by sector) will be made for a one year period. Note that this will need 'n+1' simulations to evaluate the influence of 'n' sectors.
- ❖ Calculation of sector-based radiative forcing will be done from aerosol constituents using appropriate aerosol

optical properties representative of regional sources.

- ❖ Model operation in 'full chemistry' mode and model prediction of a suite of gaseous and aerosol constituents will be explored in a second programme phase.
- ❖ Simulations with sector-tagged emissions in 'full-chemistry' model in second programme phase. Calculation of sector-based radiative forcing from gas-phase and aerosol pollutants.

3.4. Understanding the influence of carbonaceous aerosols on regional climate change and climate futures through general circulation modelling

3.4.1. Objectives

- ❖ Understanding GCM predicted aerosol radiative forcing over the Indian region in hindcast and evaluation of sources affecting aerosol radiative forcing.
- ❖ Understanding the uncertainty in GCM predicted precipitation at different atmospheric concentration levels of aerosols.
- ❖ Understanding aerosol perturbation of long-term trends in precipitation.
- ❖ Understanding aerosol-mediated changes in snow albedo, radiative forcing and surface temperature over snow surfaces, specifically in the Himalaya.
- ❖ To understand the proximate and remote effects of aerosols.
- ❖ To understand the effect of different aerosol species.
- ❖ To understand how different vertical distributions of aerosols can have an impact on precipitation and climate.
- ❖ To understand the role of aerosol indirect effect (as CCN) and its interaction with the direct effect (radiative).

3.4.2. Methodology and approach

1. Evaluation of available carbonaceous aerosol observations over India. Examination of the sensitivity of the chosen model(s) and ability to reproduce measurements on spatial and seasonal scales. Ability of models to reproduce surface to lower troposphere variation in measured carbonaceous aerosol concentrations.
2. Through NCAP, the inclusion of aerosols in climate models will be undertaken. Multiple GCMs (AGCMs or coupled models) will be identified, which have the ability to reproduce the Indian monsoon accurately. These can include the ECHAM5-HAM, CCSM, NCMRWF, LMD-INCA and other GCMs. Such models

- will be assessed for their ability to accurately represent aerosol microphysics, mixing state, optical properties and interaction with clouds.
3. Groups using different models will set up collaborations, as needed, with model developers. Porting and operationalisation of the model will be undertaken on the IITM Climate Centre computing facility machine and the machines at Computational Research Laboratory, Pune. All groups will need dedicated broad-band access to the IITM and CRL machines. Exchange visits of students and / or PIs to partner institutions will be undertaken for hands-on training on using models. HPC support must be provided by the IITM and CDAC groups for operationalising models on the IITM computing facility. HPC support must be obtained through “compute on demand” arrangement with the group at Computational Research Labs is for operationalising models on the CRL machine.
 4. Evaluation of GCM predicted aerosol radiative forcing (in four to five selected AGCMs or coupled models) in hindcast for ten years (2000-2010) and 25 years (1985-2010), using a projected emissions inventory. Evaluation against available satellite derived aerosol products.
 5. Evaluation of AGCM (with prescribed SSTs) or coupled model predicted precipitation at two different atmospheric concentration levels of aerosols in hindcast for ten years (2000-2010) and 25 years (1985-2010).
 6. Separately study the effect of different aerosol species (e.g., dust, carbon, sea-salt, sulfate) on precipitation.
 7. Selectively include and exclude aerosols from different regions of the world to see the local and remote impact of aerosols. This is necessary because in future, concentration of aerosols can change (increase or decrease) heterogeneously in space and time due to industrial development in one hand, and increasing effort to cut emission on the backdrop of climate change.
 8. Vertical distribution of aerosols should be incorporated carefully in a numerical model to understand the impact of heating profile on climate and travelling waves like Madden-Julian Oscillation.
 9. Improve existing cloud microphysical schemes that include aerosols. Include this scheme in a GCM with aerosol radiative effect and assess the compound impact on climate.
 10. Long term forecast simulations in ensemble mode (50 y simulations, 5 run ensemble) and evaluation of trends in precipitation at two different atmospheric concentration levels of aerosols.
 11. Long term forecast of climate variables using simulations with projected aerosol emissions will be made in the second phase of the project.

IV

Implementation Design and Coordination

1. Institutional arrangement

1.1. Institutional mechanism:

The programme is visualized as a multi-institutional and multi-agency project. The major departments associated with the studies include the Ministry of Environment & Forests, Ministry of Earth Sciences, Ministry of Science and Technology, Indian Space Research Organisation (ISRO) and their associated agencies. The other institutions involved are the universities, research institutions, premier scientific establishments, colleges and non-governmental agencies to undertake the various components of the programme which principally consists of aerosol observations and modeling of the impacts of carbonaceous aerosols (black carbon).

Each of the associated partners will participate in the project activities and perform roles assigned to them and will essentially serve as **Lead Institutions, Associated Institutions** and **Outreach Institutions** (see list of identified institutions in the Annexure). While each institution will work in its domain area, some of the institutions will perform functions as assigned to them as Lead, Associated or as an Outreach entity. The Lead Institution will coordinate the activities of the Associated Institutions, whereas the Associated Institutions shall be engaged in observations and analysis.

1.2. Implementation design:

The project implementation design will consist of a Programme Implementation Apex Committee under the chairmanship of Hon'ble Minister of Environment and Forests, with representatives from the Ministry of Environment & Forests, Ministry of Earth Sciences, Department of Space, Department of Science and Technology and other members drawn from the scientific community.

A Scientific Steering Committee (SSC) will be chaired by

Prof. J. Srinivasan, Indian Institute of Science. The other members may include Working Group Chairmen and other experts.

There are three major aspects (a) aerosol monitoring (b) glaciers and (c) modeling. The Scientific Programme Coordination Committee (SPCC) will supervise the overall science. There will be three working groups (WGs) with a WG chairman for each group. Major responsibilities such as aerosol monitoring (network observations), glacier studies, and modeling will be assigned to these three WGs. Each working group will have five to seven members. WG chairman and members in each WG should be experts in the respective research topic.

2. Coordination

The MoEF will undertake the administrative coordination of the entire project. The Ministry of Earth Sciences, Indian Space Research Organization (DoS) and the Ministry of Science and Technology shall coordinate the activities of institutions under their administrative charge. These Ministries shall devise appropriate arrangements in their headquarters to coordinate the activities. The entire project shall be coordinated through the apex Steering Committee at the MoEF.

The Indian Institute of Science shall be responsible for scientific coordination. The Indian Institute of Science shall establish a coordination cell with appropriate personnel and shall be responsible for coordination of implementation of the scientific activities among the various participating institutions.

3. Institutions identified for the programme

The institutions identified for participation in the programme have been listed in the Annexure.

Conceptual Framework for the Implementation and
Coordination the Science Programme





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Annexure

Institutions identified for the programme

Ministries/ Departments

1. Ministry of Environment and Forests, Government of India
2. Indian Space Research Organization, Department of Space, Government of India
3. Department of Science and Technology, Government of India
4. Ministry of Earth Sciences, Government of India
5. Council for Scientific and Industrial Research, Government of India

Lead Institutions

6. Andhra University, Visakhapatnam.
7. Aryabhata Research Institute for Observational Sciences (ARIES), Nainital.
8. Divecha Centre for Climate Change, Indian Institute of Science, Bangalore.
9. Indian Institute of Management, Ahmedabad
10. Indian Institute of Technology, Delhi
11. Indian Institute of Technology, Kanpur
12. Indian Institute of Technology, Mumbai
13. Indian Institute of Tropical Meteorology, Pune.
14. National Physical Laboratory, New Delhi
15. National Remote Sensing Centre, Hyderabad
16. Physical Research Laboratory, Ahmedabad.
17. Snow and Avalanche Study Establishment (SASE), Chandigarh.
18. Space Physics Laboratory, VSSC, ISRO, Thiruvananthapuram.

Associated Institutions

19. Banaras Hindu University, Varanasi
20. Birla Institute of Scientific Research (BISR), Jaipur
21. Birla Institute of Technology, Mesra
22. Birla Institute of Technology, Ranchi
23. Central Arid Zone Research Institute, CAZRI
24. Centre for Development of Advanced Computing, Pune
25. Cochin University of Science And Technology (CUSAT), Kerala
26. Computational Research Laboratory, Pune
27. Dayalbagh University, Agra
28. Dibrugarh University, Dibrugarh
29. GB Pant Institute of Himalayan Environment and Development, Almora
30. Geological Survey of India, Kolkata
31. Goa University, Goa
32. Himachal Pradesh Remote Sensing Cell, Shimla
33. Hindustan University, Kelambakkom, Chennai
34. India Airforce, Nalia
35. Indian Automotive Research institute, Pune
36. Indian institute of astrophysics, Hanle

37. Indian Institute of Remote Sensing, Dehradun
38. Indian Institute of Science Education and Research, Bhopal
39. Indian Institute of Space Science and Technology (IIST), Thiruvananthapuram
40. Indian Institute of Technology, Chennai
41. Indian Institute of Technology, Indore
42. Indian Institute of Technology, Kharagpur
43. Indian Institute of Technology, Roorkee
44. Indian Meteorological Department, Minicoy
45. Indian Meteorological Department, New Delhi
46. Indian Space Research Organisation, Bangalore
47. Indian Statistical Institute, New Delhi
48. Institute of Minerals Materials Technology (IMMT), Bhubaneswar
49. International Management Institute, Kolkata
50. ISTRAC, Port Blair
51. Jawahar Lal Nehru University, New Delhi
52. Maulana Azad National Institute of Technology, Bhopal
53. National Remote Sensing Centre, Hyderabad
54. North Eastern Space Application Centre (NESAC), Shillong
55. Patiala University, Patiala.
56. Regional Remote Sensing Service Centres , Kharagpur
57. Regional Remote Sensing Service Centres, Nagpur
58. School of Planning and Architecture, Bhopal
59. Shri Krishnadevaraya University, Anantapur
60. Sikkim State Council of Science & Technology, Department of Science & Technology and Climate Change
61. Space Applications Centre (SAC), Ahmedabad.
62. Tata Institute of Fundamental Research, National Balloon Facility, Hyderabad
63. Wadia Institute of Himalayan Geology, Dehradun

Outreach Institutions

64. Ahmednagar College, Maharashtra
65. B.R. Ambedkar University, Agra
66. Deen Dayal Upadhyay Gorakhpur University, Gorakhpur
67. Gogte-Joglekar College, Ratnagiri, Maharashtra
68. Hemwati Nandan Bahuguna Garwal University
69. Jammu University, Jammu
70. Kannur University, Kerala
71. Karnataka University, Dharwad.
72. Kashmir University, Srinagar
73. Kokan Krushi Vidyapith, Raigarh, Maharashtra
74. Krishna University, Machilpatnam
75. Manipal University, Imphal
76. Maulana Azad National Institute of Technology and SPA, Bhopal
77. Mohan Lal Sukhadia University, Jaisalmer
78. Mohan Lal Sukhadia University, Udaipur
79. Motilal Nehru National Institute of Technology, Allahabad
80. National Environmental Engineering Research Institute
81. National Institute of Technology, Raipur
82. National Institute of Technology, Warangal
83. NTR University, Vijayawada
84. Oil and Natural Gas Corporation, Mumbai
85. Patna University, Patna
86. Rani Durgavati Viswavidyalaya, Jabalpur
87. Rubber Research Institute, Kottayam, Kerala
88. Saurashtra University, Rajkot

89. Sharda University, Grater Noida
90. Sikkim University, Sikkim
91. Simla University, Dharamsala
92. Solapur University, Solapur
93. SRM University, Chennai
94. Tamil Nadu Agricultural University, Ooty
95. Tripura University, Agarthala
96. University of Allahabad; National Institute of Technology, Allahabad
97. University of Kashmir, Srinagar
98. University of Mangalore, Mangalore
99. University of North Bengal, Darjeeling/Siliguri.
100. Vikram University, Ujjain
101. Yogi Vemana University, Kadappa

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