सत्यमेव जयते

National Carbonaceous Aerosols Programme

COALESCE Project

CarbOnaceous AerosoL Emissions, Source apportionment & ClimatE Impacts

Ministry of Environment, Forest & Climate Change

Indian Institute of Technology Bombay

Credits

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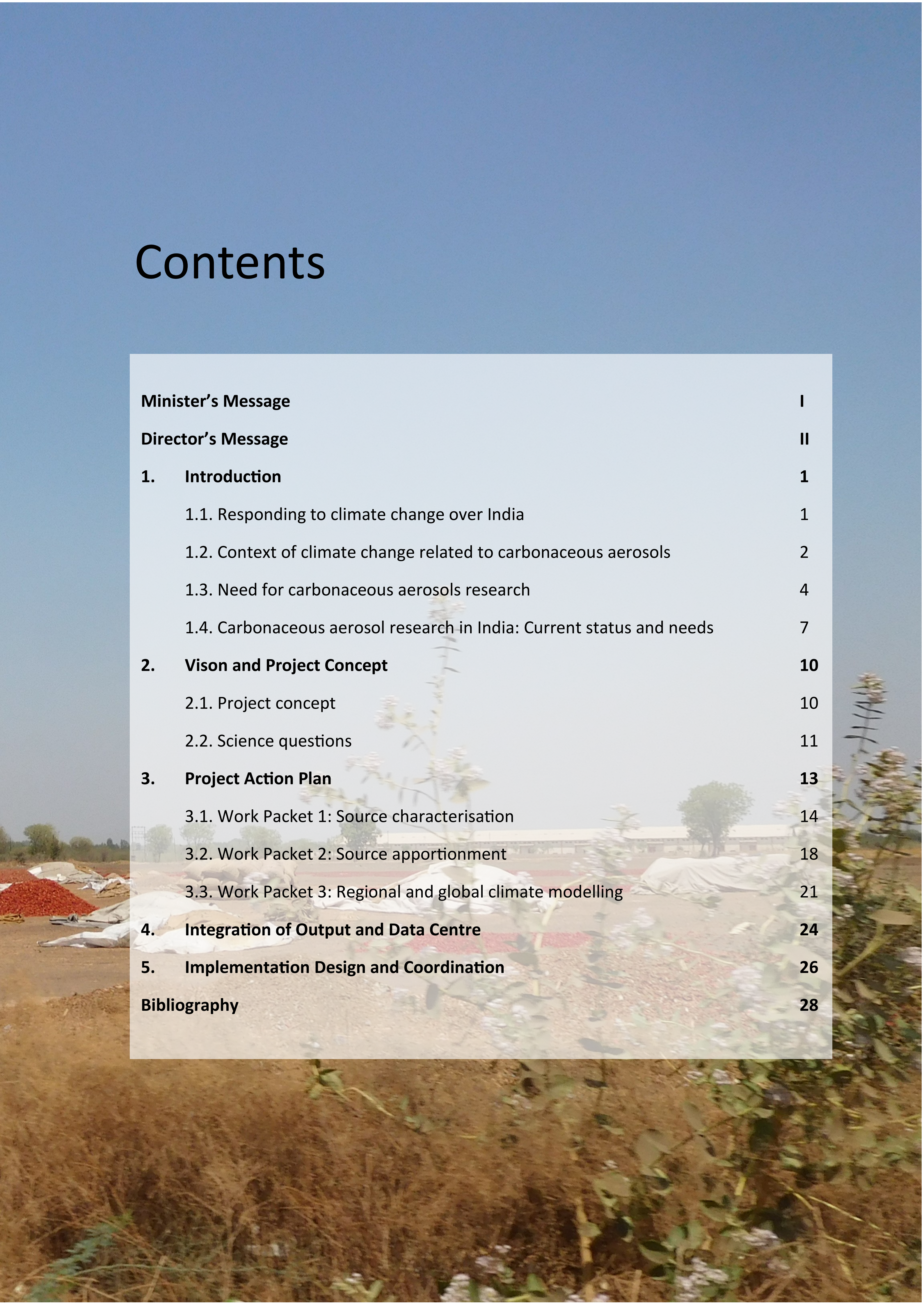

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Dr. Harsh Vardhan

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भारत सरकार
पर्यावरण, वन एवं जलवायु परिवर्तन मंत्री
GOVERNMENT OF INDIA
MINISTER OF ENVIRONMENT, FOREST & CLIMATE CHANGE

MESSAGE

Climate change already has observable effects on the environment. Anthropogenic or human related activities which lead to emissions of greenhouse gases and short-lived pollutants and land use change have resulted in discernible impact on temperature and rainfall and on coastal and mountain ecosystems. Effects of climate change which were predicted in the past by scientists are now occurring: loss of sea ice, accelerated sea level rise, and more frequent occurrence of intense weather events.

India's Nationally Determined Contributions (NDC) submitted to United Nations Framework Convention on Climate Change (UNFCCC) which inter-alia, embodies reduction of emission intensity of our GDP by 33 to 35 percent by 2030 from 2005 level, is a testimony of our determination and commitment to global environmental concerns.

The government is committed to enhancing investments in development programmes in sectors vulnerable to climate change, particularly agriculture, water resources, Himalayan region, coastal regions, health and disaster management. We have a Strategic Knowledge Mission for capacity building and training of scholars and researchers to generate new knowledge to underpin government decision-making.

The National Carbonaceous Aerosols Programme- Carbonaceous Aerosol Emissions, Source Apportionment & Climate Impacts (NCAP-COALESCE) project, a comprehensive research programme involving a consortium of 17 Research Institutions coordinated by IIT Bombay is a step in this direction. It is initiated by the Ministry of Environment, Forest and Climate Change and aims at improving our understanding of regional carbonaceous aerosols over India, in terms of major sources, magnitude of emissions, their atmospheric fate and deposition, and their impacts on clean air and climate.

I am hopeful that this project will encourage our scientists to address important questions, generate new and impactful knowledge and produce research outputs which are second to none in the world. I am confident that this project will become a knowledge repository to facilitate government decision making and to support climate negotiations.

Harsh

(Dr. Harsh Vardhan)

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Devang V. Khakhar, Director
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July 4, 2017

DIRECTOR'S MESSAGE

The Inter-disciplinary Programme (IDP) in Climate Studies, initiated at the Indian Institute of Technology Bombay, in January 2012, has grown into a mature academic unit addressing education and research related to climate change. Over the years, the programme has seen a spurt in research projects, high impact publications and new partnerships with reputed academic and research institutions.

As part of India's National Climate Action Programme, I welcome the launch of the NCAP-COALESCE project (National Carbonaceous Aerosols Programme - Carbonaceous Aerosol Emissions, Source Apportionment and Climate Impacts project) funded by the Ministry of Environment, Forests and Climate Change.Under the leadership of IIT Bombay's IDP in Climate Studies, this multi-institutional, coordinated project, would enable teamwork in cutting-edge fundamental research to understand the sources, fate and impacts of carbonaceous aerosols, on climate change in the Indian region.The project would be a key step to build a strong knowledge base for India related to short lived climate pollutants, including carbonaceous aerosols, as part of India's broad commitment to climate action.

Importantly, the project would also contribute towards building scientific capacity, through training of M.Sc., M.Tech. and Ph.D. students as well as the creation of infrastructure and systems at the participating institutions.

I am confident the project would strengthen scientific networks and provide key new knowledge to underpin government decision making in regard to climate change. I wish the NCAP-COALESCE scientific consortium and the project all success.

(Devang Khakhar)


Guilhem Vellut

1. Introduction

1.1. Responding to climate change over India

It is now accepted with certainty that human activities influence global climate change. Difficulties persist in our understanding of the climate change impacts on regional and sub-regional scales. There is a need for the increase in robustness of climate change predictions and information, to facilitate a better understanding of regional scale climate change and climate futures. To address some of these concerns, the Indian Network for Climate Change Assessment (INCCA) was launched on 14th October 2009, as a network-based scientific programme, bringing together scientists from over 125 Indian government and non-government institutions, universities and industry organisations working on issues of climate change.

The INCCA has been conceptualised as a network-based scientific programme designed to address concerns of regional climate change. Initially, it was proposed to undertake the following actions:

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

The National Carbonaceous Aerosols Programme (NCAP) was launched by the Ministry of Environment, Forest and Climate Change (MoEFCC), on March 29, 2011, to address carbonaceous aerosol effects on climate change.

1.2. Context of climate change related to carbonaceous aerosols

Anthropogenic or human related drivers of climate change include activities which lead to emissions of greenhouse gases and other climate change agents, or changes in land-use & land-cover patterns that can affect carbon dioxide uptake and precipitation recycling by the terrestrial biosphere. Several radiatively active compounds in Earth's atmosphere are affected by chemical and physical processes, including (1) interaction with terrestrial constituents and water (wet removal and dry deposition) and (2) reactions initiated by solar radiation (photolysis). These processes are characterized by strong temporal or spatial variability, leading to impacts on widely varying scales. These compounds are collectively identified as short-lived climate pollutants (SLCPs), with lifetimes in the atmosphere varying from a few days to a few decades. Carbonaceous aerosols form a subset of such SLCPs.

Carbonaceous aerosols are constituents of the atmospheric aerosol or particulate matter. Atmospheric aerosols are fine particles, which remain suspended in air; they include pollution particles and those of natural origin, like dust and sea-salt. It is known that such particles are transported long distances from their locations of emission, and exert impacts even on inter-hemispherical scales. Historically, atmospheric particulate matter has been of concern in regard to air pollution and its effects on human health. Carbonaceous aerosols include:

(i) non-reactive, non-volatile carbon forms (elemental carbon, EC; light absorbing black carbon, BC; and carbonates),

(ii) mainly volatile and/or reactive organic carbon (OC) and

(iii) light absorbing organic carbon fractions or brown carbon (BrC).

The term "carbonaceous aerosol," which corresponds to all carbonaceous components organic and elemental, light absorbing and light scattering, is absolute, and not operationally defined.

Over the last few decades, influence of carbonaceous aerosols particularly black carbon, on the climate system is beginning to be understood. It is now acknowledged that:

- Atmospheric black carbon leads to net warming of the atmosphere; the effect terminates quickly because of its short atmospheric lifetime of about a week.

- Black carbon deposition on snow and ice causes positive radiative forcing; however, the role of carbonaceous aerosols in melting of glaciers is still highly uncertain.
- Regional circulation and rainfall changes may occur from aerosol forcing, particularly that from black carbon; however, responses to the complex forcing are not robustly simulated by global models.
- Species co-emitted with black carbon (organic carbon, sulphates and others) exert significant climate forcing, which must be treated alongside.
- Air quality regulations that reduce sulphate particles (e.g., shifts from coal burning), unintentionally reduce their masking of GHG warming, a cooling which results from their scattering of radiation. It is thus important to concomitantly target emission reductions of warming SLCPs.
- Continuous reductions in emissions of BC and other short-lived climate pollutants could be used to manage the trajectory of climate forcing, while they do not offset long-term climate change from GHGs.

Global models underestimate atmospheric absorption by black carbon in different world regions, in comparison with remote sensing observations. This is especially significant in South Asia (Figure 1).

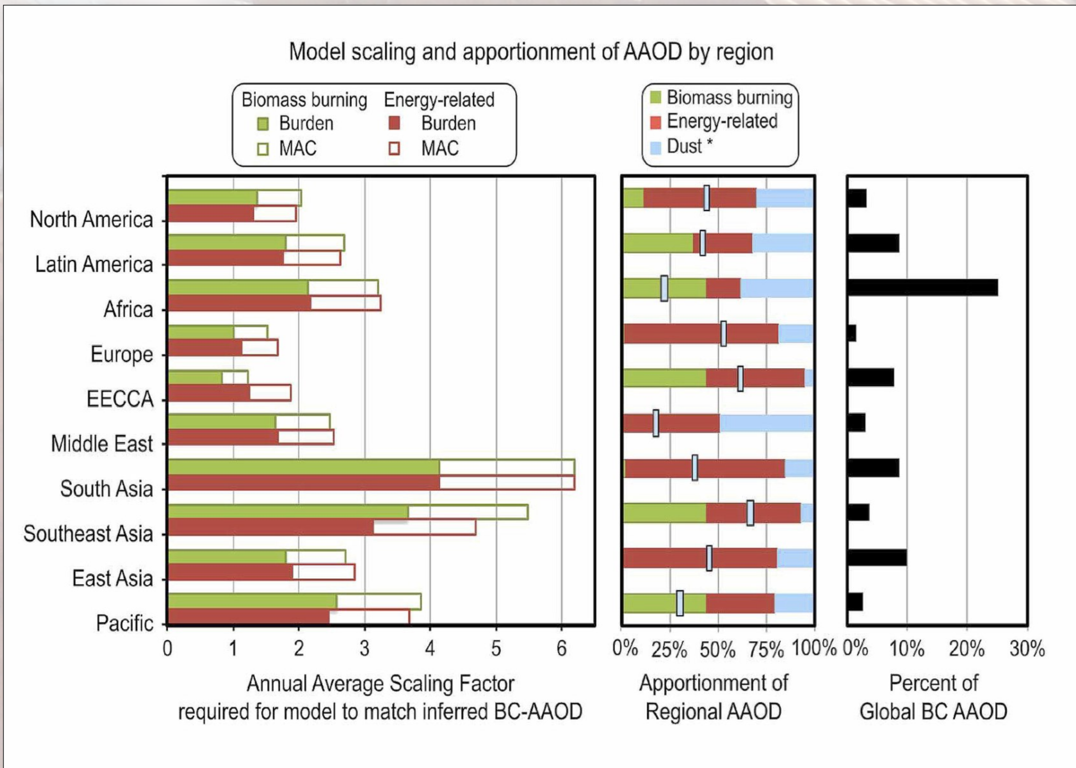

Figure 1. GCM under-prediction of BC over South Asia [Bond et al., 2013].

1.3. Need for carbonaceous aerosols research

A comprehensive research programme is needed to further our understanding of regional carbonaceous aerosols over India, in terms of major sources, magnitudes of emissions, their atmospheric fate and deposition, and their impacts on clean air and climate. Furthermore, robust measurements and modelling studies are needed to identify climate impacts from carbonaceous aerosols, and opportunities to offset them through strategic mitigation actions (Figure 2).

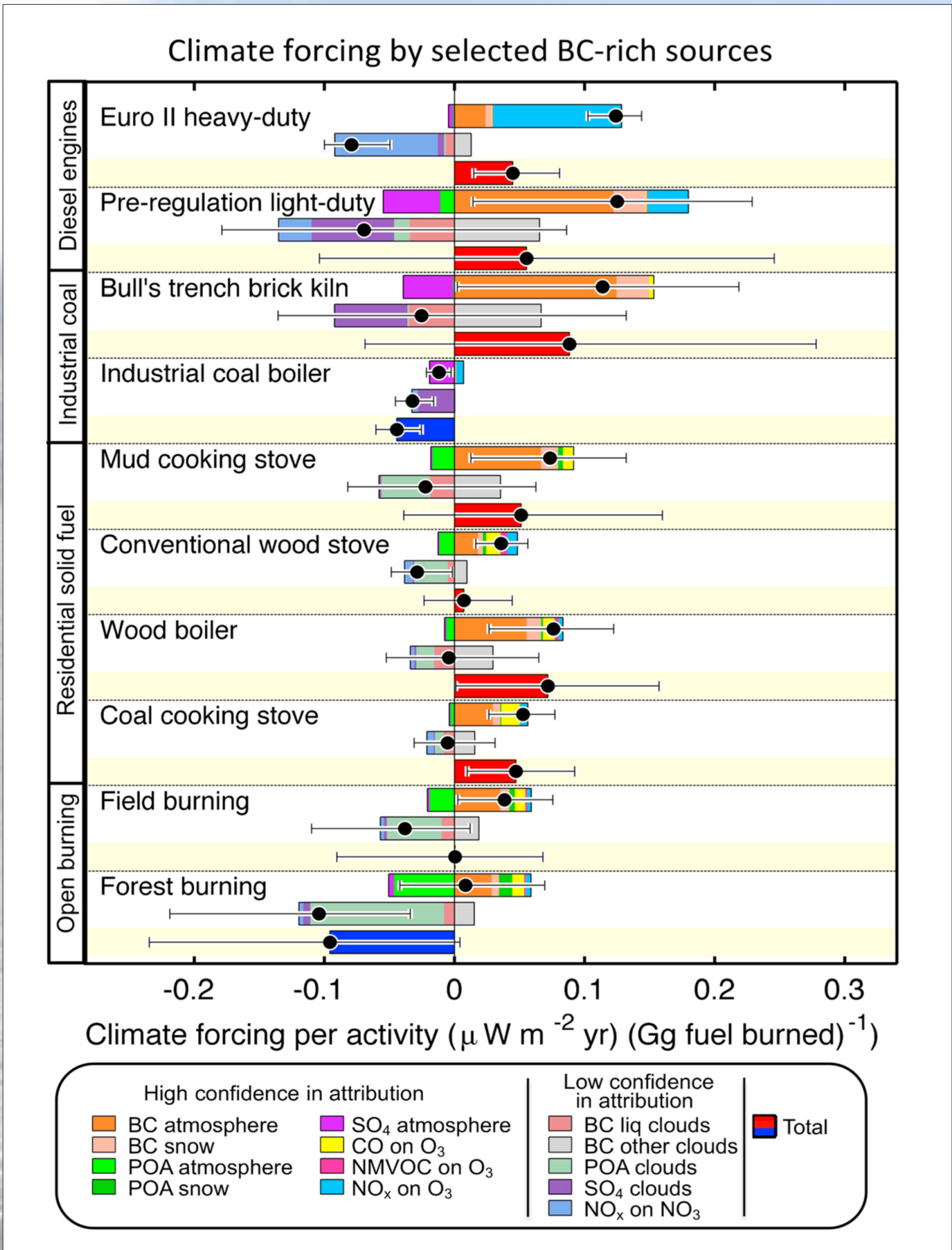

Figure 2. Climate forcing by BC-rich sources [Bond et al., 2013].

There is recent policy attention, in the international arena, to the opportunity to reduce SLCP and black carbon emissions.

- The G8 declaration targets GHG reductions and, in addition, is committed to "...taking rapid action to address other significant climate forcing agents, such as black carbon." (Italy, 2009).
- The Arctic Council, recognizing that reduction in BC emissions "...have the potential to slow the rate of Arctic snow, sea ice and sheet ice melting in the near-term...," encouraged the eight member states to implement black-carbon mitigation measures (Greenland, 2011).
- In the United States of America, a bill was adopted, requiring a study of the sources, climate and health impacts, and mitigation options for black carbon, both domestically and internationally (The United States of America, 2015).
- In February 2012, the Climate and Clean Air Coalition of the UNEP was formed. In partnership with CCAC, several world nations have initiated action on short-lived pollutants-in particular, BC, methane, and hydrofluorocarbons. Under environmental protection and air quality laws, several countries have now included specific action which targets SLCPs (France, 2014).
- China's new Environmental Protection Law proposed an ambitious carbon intensity goal and a timeline for a nationwide carbon trading system. New amendments have expanded the list of pollutants to also include particulate matter, volatile organic compounds, and greenhouse gases (China, 2013).
- In 2016, among Nationally Determined Contributions submitted to the UNFCCC, eight countries have specifically addressed SLCPs . Mexico has proposed a formal target which "implies a reduction of 22% of GHG and 51% of Black Carbon with respect to year 2000" (United Nations, 2016).

Strong scientific underpinnings are needed for proposing carbonaceous aerosol emission reduction through establishment of robust links between their atmospheric abundance and regional climate stress, along with potential benefits from mitigation.

Atmospheric carbonaceous aerosols significantly change the energy balance of Earth's surface and atmosphere and alter cloud properties, thereby affecting climate. Black carbon strongly absorbs radiation and leads to atmospheric heating, while organic and brown carbon (totally or largely scattering constituents) scatter radiation and lead to atmospheric cooling. Climate effects result from aerosol radiative forcing or change in downward radiation flux.

The resulting non-homogeneous heating and cooling, exerted by carbonaceous aerosols, affect circulation patterns and atmospheric moisture levels which can change distribution and trends in rainfall. In addition, aerosol modification of cloud microphysical properties (number concentration and size distribution of drops), leads to alteration of cloud reflectivity and thermodynamic processes by which rainfall occurs. The deposition of absorbing aerosol particles including black carbon and dust decreases the reflectivity of snow and ice surfaces, causing radiative forcing which has high efficacy.

Carbonaceous aerosol emissions arise primarily from energy use (mainly from incomplete combustion of fuels in traditional technologies in the residential and industrial sectors, and from diesel transport) and the burning of forests, grasslands and agricultural residues in fields.

Emission sources and sectors vary across world regions, with a dominance of individual combustion sources (in the residential sector) in Asia and Africa, whose emissions are not well characterised. These emissions lead to air-quality degradation and related health risks on local to regional scales and to climate impacts on regional to global scales. Thus, there are many gaps in our understanding of carbonaceous aerosol emissions, properties, and climate effects specifically on regional scales.

1.4. Carbonaceous aerosol research in India: Current status and needs

The study of aerosols, in general, has a long history in India with long term observations of atmospheric turbidity under the auspices of the India Meteorological Department. Since the 1980s, there has been a focus on networks for multi-wavelength radiation monitoring, with a view to understanding aerosol climatology, operated under the aegis of the Indian Space Research Organisation's Geosphere Biosphere Programme. Important field experiments have been made in campaign mode to understand aerosol physics, chemistry and radiative effects over ocean regions and over the Indian subcontinent.

There are numerous individual studies of measurements of black carbon at urban, rural and high altitude sites. Long term observations of black carbon aerosols have been initiated. In addition, an initiative for study of the impact of black carbon on snow surfaces has also been established.

At present there is significant disagreement on the magnitude of carbonaceous aerosol emissions from India, along with a large uncertainty in the estimates. Further, we have very limited understanding on links between microphysical, chemical and optical properties of these aerosols.

Sources, whose emissions are rich in carbonaceous aerosols, can be grouped into a small number of source categories. These include:

(i) Traditional technologies in the residential sector (for cooking and lighting),

(ii) Brick production and informal industry,

(iii) Field burning for disposal of agricultural residues and other forms of open burning, and,

(iv) On-road diesel vehicles.

In terms of understanding source emissions, there have been isolated studies to measure emission factors of carbonaceous aerosols from sources like biomass cooking stoves and brick kilns in India. However, there are only a few measurements worldwide, with a need for in-field measurements under actual operating conditions.

Building emission inventories with a high level of detail, for use as research and regulatory tools requires measurement of source emission factors. Other information gaps include the amounts of biomass fuel combusted, and the type of technology or burning in the residential and informal industry sectors. We also lack data on the amount of agricultural residues burned in fields and carbonaceous aerosol emission factors from this source.

The understanding of quantitative source influence, through source apportionment studies has largely been limited to urban sites, specific locations or regions. These studies cite limitations including study design unsuitable for source apportionment through receptor modelling methods, too few samples and chemical species, lack of signature compounds including organic molecular markers, leading to poor source resolution.

Understanding climate impacts of carbonaceous aerosols need modelling studies using fully-coupled chemistry climate models, with validated emissions inventory inputs. Modelling studies over the Indian region are able to capture the large spatial and seasonal variations of aerosols but typically underestimate their magnitude. There is still high uncertainty in our understanding of regional radiative effects of carbonaceous aerosols and their effects on clouds and rainfall. Atmospheric transport processes influencing deposition of carbonaceous aerosols on sensitive ecosystems, particularly snow surfaces in the Himalaya, also need better understanding.

Even though examples of long-term and short-term studies and monitoring programmes exist, there is an urgent need to develop a coordinated, national-level programme specifically targeting regional climate impacts arising from carbonaceous aerosols, under the aegis of the Indian Network for Climate Change Assessment (INCCA). The fundamental research premise of NCAP-COALESCE project is to understand the origin and fate of carbonaceous aerosols, and their role as drivers of regional climate change over India.

To address these needs, the Ministry of Environment, Forest and Climate Change decided to launch a project on “Carbonaceous Aerosol Emissions, Source Apportionment and Climate Impacts” under the National Carbonaceous Aerosols Programme. The NCAP-COALESCE project (**C**arb**O**naceous **A**eroso**L** **E**missions, **S**ource apportionment and **C**limat**E** Impacts), is a constituent activity of the Climate Change Action Programme of the country. It is envisaged as a multi-institutional, coordinated project, with the following goals:

1. To understand the sources, fate, and impacts of carbonaceous aerosols, on climate and air quality, in the Indian region through interdisciplinary research.
2. To reduce uncertainties in our understanding of the impacts of carbonaceous aerosols on regional scales over India through the adoption of robust methodologies.
3. To inform the scientific community, policy makers and the public regarding carbonaceous aerosol influence on climate change and climate stresses, and their implications.
4. To promote training and learning about aspects of aerosol measurement and modelling through workshops on research methods.

2. Vision and Project Concept

This project envisages a coordinated, national-level programme, specifically targeting regional climate impacts arising from carbonaceous aerosols.

2.1. Project concept

The project concept is based on integrating "bottom-up" approaches (emissions inventory driven regional climate modelling), with "top-down" constraints (source apportionment through multivariate modelling using in-situ measurements) to reduce uncertainties in understanding regional climate change impacts of carbonaceous aerosol (Figure 3).

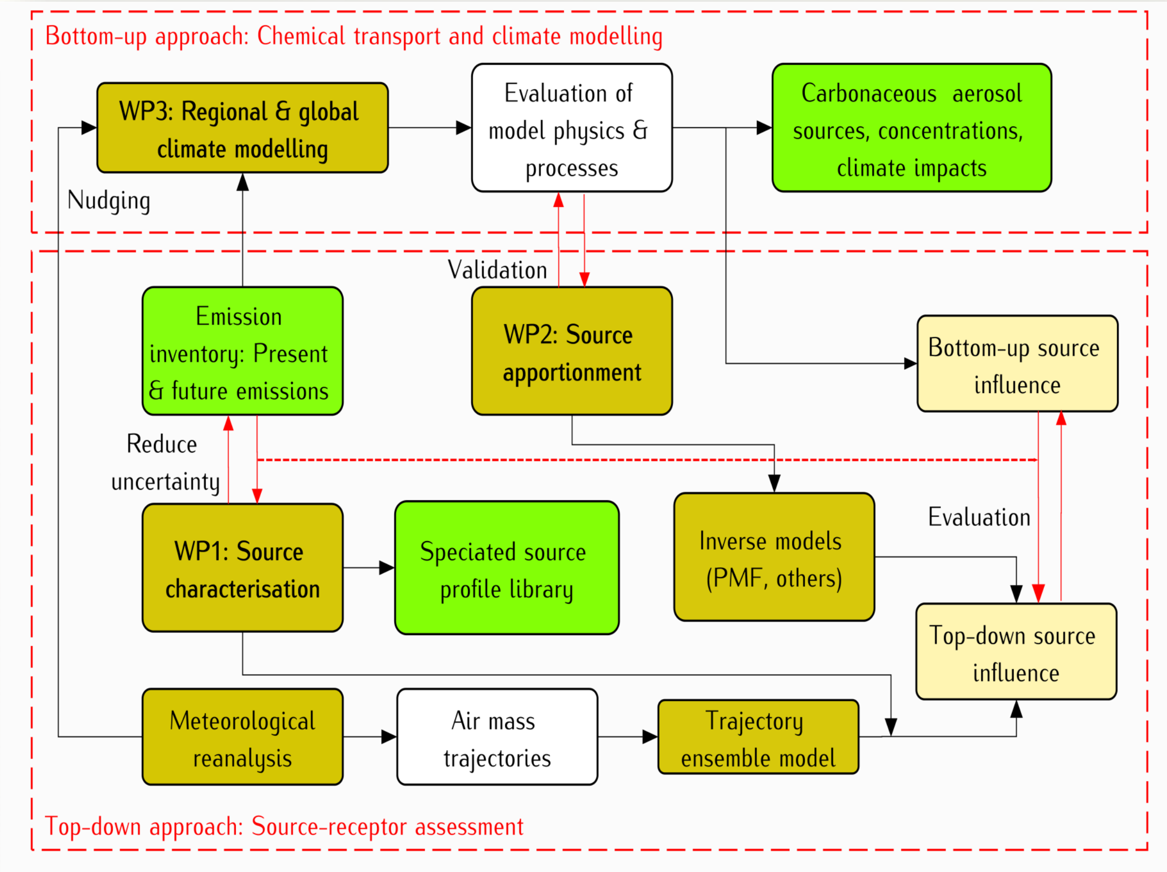

Figure 3. The project concept is based on an integration of top-down and bottom- up approaches.

“Bottom-up” approaches use the development and deployment of an emissions inventory in atmospheric model simulations, which accounts for atmospheric transport, sinks and chemical conversion on regional scales. The outcome is an estimate of aerosol influence on climate variables like the radiation balance, temperature, and rainfall, which can be estimated by source type. Uncertainties in the magnitude and spatial distribution of emissions and in differences among models, contribute to uncertainties in the predicted effects.

“Top-down” approaches use in-situ measurements and receptor modelling, which exploits measurements of detailed chemical composition (mass, elements, ions, and organic and elemental carbon), sometimes in combination with emission composition, specific markers, satellite data, and trajectory ensembles. The outcome is the identification of the emission source types and their quantitative influence on carbonaceous aerosol concentrations.

In this project, a harmonization between these two approaches will be made to develop an emission inventory of carbonaceous aerosols for India, with bounded uncertainties. Information from both methods will be used to arrive at a rational understanding of sources which influence regional carbonaceous aerosol abundance over India. A suite of regional climate models, and some general circulation models will deploy the emission inventory to estimate carbonaceous aerosol effects on radiation, cloud properties, temperature, and rainfall over India.

2.2. Science questions

The NCAP-COALESCE project will address the following scientific questions, as a first step to understanding climate change over India from carbonaceous aerosols:

1. What are the major emission sources of carbonaceous aerosols in India; what is the magnitude (seasonal and regional distribution) of emissions from these sources?
2. How does carbonaceous aerosol abundance over India change by season and region; what is the quantitative contribution of different emission sources?
3. What are the effects of carbonaceous aerosols and co-emitted species on regional climate variables over India, including radiative forcing, cloud properties, temperature, and rainfall?

Within these three broad themes, multiple research objectives will be addressed:

a. Measurement of field emission factors of BC and co-emitted species from major sources of regional importance (e.g., biomass stoves, kerosene lamps, brick production, on-road diesel transport, agricultural residue burning). Identification of sources which emit the darkest (net warming) particles.

b. Measurement of emission factors of light absorbing organic carbon or brown carbon from key emitting sources. Survey-based studies to estimate activity rates in the use of different fuels, technologies, and practices in key carbonaceous aerosol emitting sectors.

c. Multivariate modelling with in-situ measurements to arrive at quantitative source apportionment of carbonaceous aerosols.

d. Distinguishing similar sources of carbonaceous aerosol emissions using chemical fingerprinting (organic markers, C-isotopes).

e. Combining source apportionment modelling with on-site meteorology and air-parcel trajectories to identify local and regional source locations.

f. Developing inverse modelling methods for inferring carbonaceous aerosol source strength from in-situ and satellite observations.

g. Conducting a regional climate model intercomparison study; identification of model physics which best simulates regional effects.

h. Numerical experiments to understand the sensitivity of climate forcing to various model parameters.

i. Understanding carbonaceous aerosol abundance, and its source apportionment, resolved by season and region, from harmonisation of multivariate source apportionment with regional climate model predictions.

j. Estimating aerosol radiative forcing over India and the contribution by carbonaceous aerosols, resolved by season and region.

k. Understanding atmospheric pathways leading to carbonaceous aerosol deposition in the Himalaya.

l. Special hypothesis including carbonaceous aerosol modification of cloud properties and rainfall, separating direct and indirect effects of carbonaceous aerosols, estimating land-surface feedback and carbonaceous aerosol effects on rainfall.

3. Project Action Plan

The implementation scheme for the NCAP-COALESCE project will revolve around three work packets, including (a) WP1 - Source characterisation (b) WP2 - Source apportionment and c) WP3 - Regional & global climate model.

Building a carbonaceous aerosol emission inventory for India would include emission factor measurement in four key sectors: residential cooking and lighting (biomass fuel cookstoves, kerosene lamps), brick production (Bull's trench kilns, clamp kilns), agricultural residue burning (in chosen districts in different regions) and on-road diesel vehicles (under different operating conditions). Full chemical speciation of the measured particles will be done to obtain emission factors BC, OC and co-emitted species. These will be combined with activity data for all sectors nationally, to develop a spatially resolved national emissions inventory.

A "top-down" approach using source apportionment models such as positive matrix factorization and other Bayesian approaches will be applied to a combination of PM mass, chemical constituents, and meteorological parameters. Measurements of fine particulate matter (PM) and its chemical constituents, measured at various regionally representative locations across India reflecting different regional source mix, will be used to determine the sources of ambient $PM_{2.5}$ in general, and carbonaceous aerosols in particular.

A modelling framework will be used, with a validated emissions inventory specifically representative of emissions in the Indian region, with evaluation against regional observations from in-situ and satellite sensors and remote sensing. A suite of global and regional climate models will be used in this project. Models will be used to examine effects on aerosol abundance (with seasonal and spatial resolution), source apportionment, total aerosol and carbonaceous aerosol radiative forcing, trends in cloud properties, and rainfall. Workflow and data transfer among the work packets would be ensured leading to an integrated output.

3.1. Work Packet 1: Source characterisation

Emission inventories are important research and regulatory tools that link energy use and technology adoption to changes in emissions. They are used as inputs to atmospheric models used to study the climate effects of changing emissions on different scales, from urban to regional, and from inter-hemispherical to global scales. Accurately estimating the magnitude of emissions at the sectoral level (e.g., industry, transport, residential or agriculture) requires dividing energy or fuel consumption into appropriate technology divisions and treating high-emitting technologies separately.

Existing Indian inventories for different pollutants and short-lived climate pollutants rely on a variety of fuel consumption databases that use different base years and varying levels of technology detail and characterization, making direct comparison difficult.

It has been reported that only about 12% of the net GHG emissions from India have been estimated from fuel consumption using a method based on sub-national disaggregation, which is compliant with the highest tier (Tier III) specified by the Intergovernmental Panel for Climate Change. Varying treatments of technology and the level of activity detail have led to disagreement among the emission estimates in different studies. Currently, Indian black carbon (BC) emission estimates differ among themselves and from global inventories by a factor of three.

It is acknowledged that uncertainties in emission inventories over South Asia are strongly linked to lack of measurements of emission factors of region specific sources and lack of information on activity related to emissions in sectors with numerous, small individual sources, like residential and informal industry.

To address these uncertainties, key efforts will be made to develop a carbonaceous aerosols emission inventory for India. This will need emission factor measurements from sources in four key sectors that emit carbonaceous aerosols: residential cooking and lighting (biofuel cookstoves, kerosene lamps), brick production (Bull's trench kilns, clamp kilns and others), agricultural residue burning, and on-road diesel vehicles (under different operating conditions) (Figure 4).

Figure 4. Key sources of Indian carbonaceous aerosol emissions.

In-field and on-road source sampling will be done (Figure 5) to obtain representative numbers of measurements (Figure 6) from different regions in India, to reflect regional differences in fuel and technology use (e.g. cookstove type, fuel used including wood, agricultural residues or dried animal manure) and differences in practices (e.g., type of agricultural residue burned in field, biomass density).

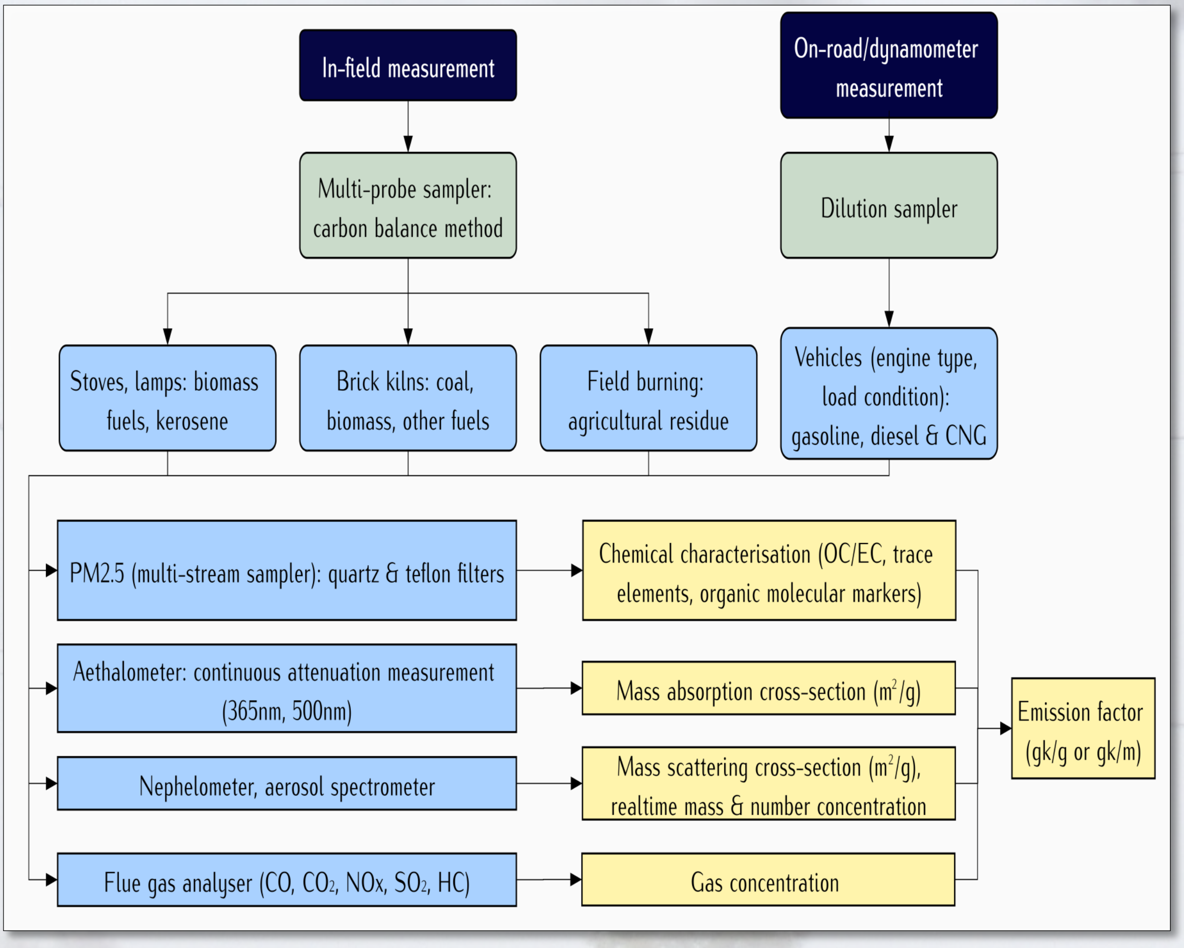

Figure 5. Emission factor measurements from key sectors emitting carbonaceous aerosols.

To ensure uniformity in measurement methods, a dilution source sampler will be designed and used by all participants. Measures will be taken during design to provide appropriate materials, dilutions and to collect numbers of samples needed on multiple filter types for various downstream chemical analysis.

Real-time measurement of aerosol size distributions and absorption will be made, along with a suite of gases, which would then be exploited to calculate quantitative emission factors.

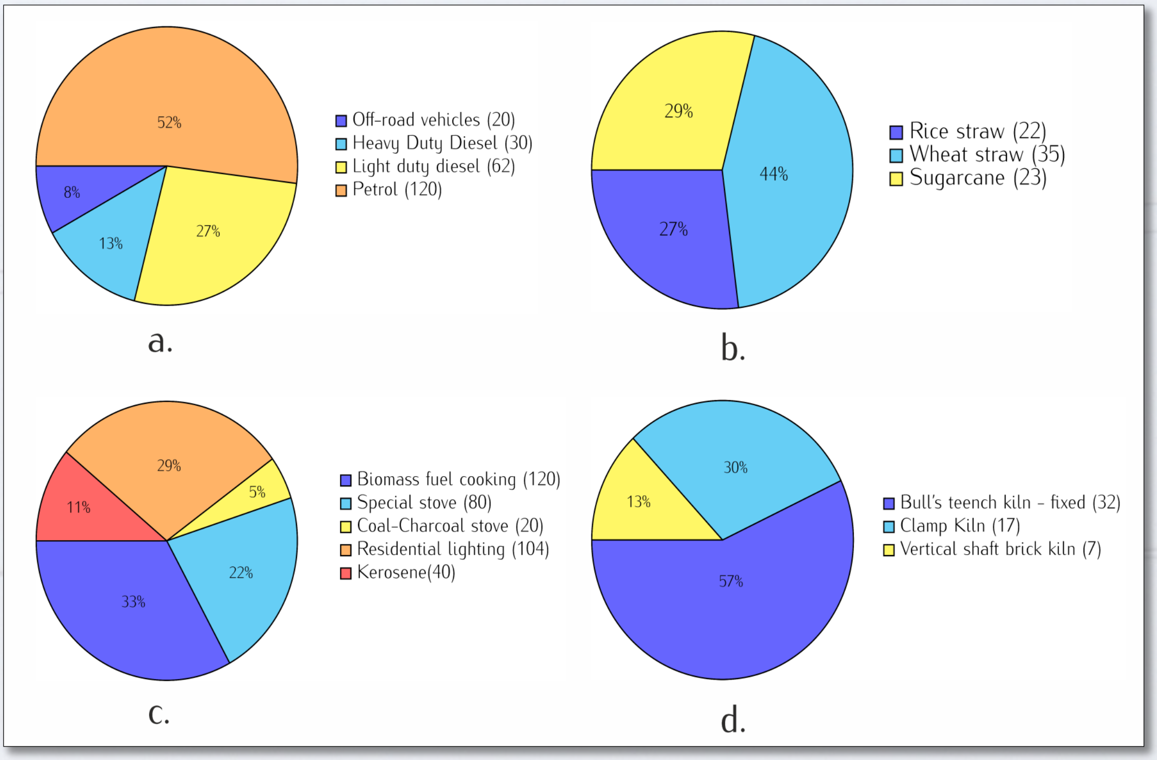

Figure 6. Emission source measurements for types of: **a.** vehicle categories (224 measurements), **b.** agricultural residue burning technologies (80 measurements). **c.** residential cooking stoves (220 measurements) and lighting technologies (104 measurements), **d.** brick kiln (60 measurements)

A source profile library will be built through a full suite of gravimetric and chemical analysis including trace elements, ions, organic and elemental carbon, on all samples. Selected samples will be subject to special molecular marker measurements including organic molecular markers and C-isotopes. Spectral absorption will be measured to understand the presence of different carbonaceous aerosol forms, including elemental carbon, light absorbing organic carbon or brown carbon and organic carbon.

To address key information gaps in activity data, methodologies will be reviewed and developed for the identified source categories. A coordinated survey campaign will be made, representative of regional variability in technologies and practices.

3.2. Work Packet 2: Source apportionment

Top-down methods for source apportionment that use atmospheric aerosol composition to deduce the influence of emission source types on measured aerosol concentration are generally known as receptor modelling. Among receptor models, the chemical mass balance (CMB) and positive matrix factorization (PMF) have seen wide application in source apportionment and air quality assessment.

These models typically exploit detailed aerosol chemical composition data (~15-25 species), sometimes including organic molecular markers, to effectively separate similar sources, like petrol and diesel vehicles. Receptor modelling may also exploit ensembles of trajectories to identify probable source regions affecting concentrations of resolved “factors”.

Principal components analysis (PCA) was used initially, while other source apportionment models were later developed, including, absolute principal components analysis (APCA), target transformation analysis (TTA), and positive matrix factorization (PMF).

While there are some isolated studies in India, receptor models have not been used effectively due to limited availability of India-specific source profiles or because of limited chemical speciation and non-specific study design. This project will use factor analytic models which require no *apriori* knowledge of the number of sources or source profiles to make a quantitative regional source apportionment.

Primarily, positive matrix factorization would be used to exploit in-situ chemical measurements made at selected locations (Figure 7), each representing a different mix of regional emission sources of carbonaceous aerosols, along with the locations which receive trans-boundary pollution transport.

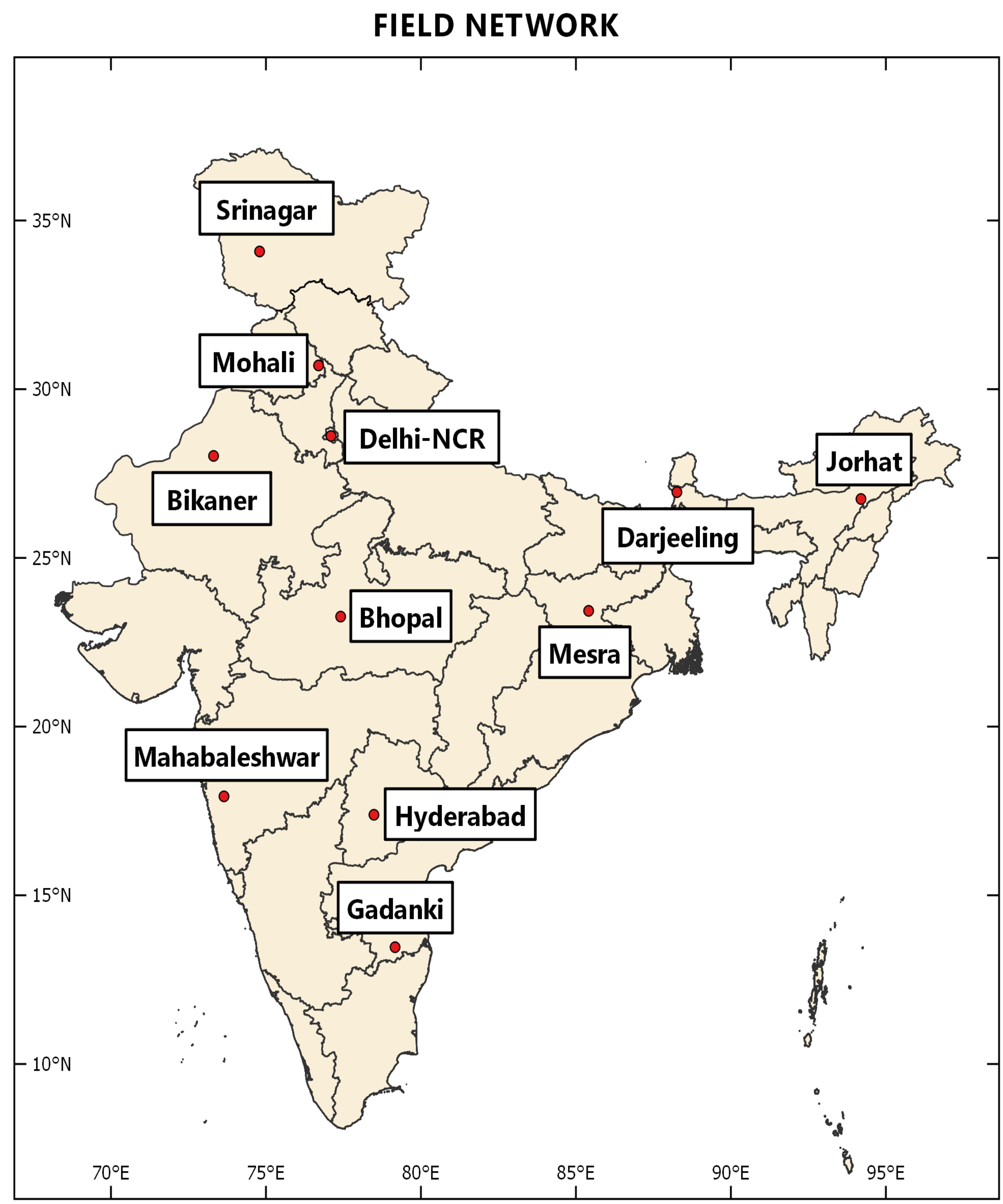

Figure 7. Location of selected sites for regional carbonaceous aerosol source apportionment. Map prepared using QGIS Geographic Information System, Version 2.14.11.

Multivariate factor analytic methods suffer from rotational ambiguity. However, in conjunction with the knowledge of likely sources/their elemental profiles (from WP1), ‘on’/‘off’ status of certain sources at a given time and meteorological data, the ambiguity can be constrained and these models can be used to obtain reliable quantitative apportionment of PM mass.

Additionally, various probability based approaches using model resolved source contributions in conjunction with air-parcel trajectory ensembles (such as Potential Source Contribution Function, PSCF) or local wind-speeds and wind directions (such as Conditional Probability Function, CPF) have been successfully used to identify the geographical locations and/or preferred transport pathways of regional and local sources, respectively. All of these approaches will be used in this study to identify the sources of $PM_{2.5}$ at the receptor site, their geographical location, and provide quantitative estimates of their contribution to $PM_{2.5}$ mass.

The incorporation of additional information, e.g., wind data (direction and speed), other parameters (like aerosol optical depth, mass absorption cross-section, special molecular markers like organics or C-isotope) in expanded multilinear models, could be valuable in identifying superior solutions. Attempts will be made to investigate tools from other approaches, including Bayesian analysis where *apriori* information about the various sources is incorporated explicitly. Exploration of matrix decomposition techniques apart from positive matrix factorization will be attempted.

A complete set of metrics/parameters that will be selected and used in this study for quality assurance – quality control (QA-QC) would include accuracy, precision, completeness, and sensitivity/detection limits. Laboratory blanks, field blanks, spikes, and replicate samples will be used as a part of the QA/QC of all analytes and incorporated in standard operating procedures followed by all participants.

3.3. Work Packet 3: Regional & global climate modelling

Bottom-up methods to understand the effects of pollutants and tracers on climate change deploy regional climate models and general circulation models to calculate 4-D concentration fields and several variables which are used to understand the impacts of these atmospheric pollutants. Estimated effects of these pollutants include aerosol radiative forcing (net change in incoming radiation) and changes in temperature, circulation patterns, cloud properties, and rainfall.

Aerosols continue to contribute the largest uncertainty to the global mean radiative forcing estimate. In terms of the response of the Earth system to aerosol forcing, different modelling studies suggest different outcomes on the Indian summer monsoon, on differing time scales. Decreases in decadal monsoon rainfall were linked to a weakening of the land-sea contrast by solar dimming or to the weakening of monsoon circulation. An early onset and increase in rainfall were suggested from high-altitude heating by absorbing aerosols over the Indo-Gangetic plain and Tibet.

Other fast responses affecting rainfall have been identified from changes induced in N-S temperature or pressure gradients or lower tropospheric stability, which need further investigation. There is also a need to understand other factors influencing rainfall perturbation, for example, land use changes, vis-à-vis those caused by aerosols, with their possible synergy or opposing interactions. The role of land surface processes has been recently found to influence a generation of precipitation within the Indian subcontinent. Links between carbonaceous aerosol mediated radiation changes and evapo-transpiration need investigation. Finally, there is still no clear understanding of the role of carbonaceous aerosols in mediating regional heating patterns and heat waves.

In this project, the first step would be to evaluate source influence on carbonaceous aerosols over India from these models with that from top-down approaches (WP2), to make changes and arrive at an optimal emissions inventory (WP1). This harmonisation will be undertaken, to arrive at a validated gridded emissions inventory of carbonaceous aerosols for India.

A modelling framework will be developed with a validated emissions inventory specifically representative of the Indian region and with evaluation against regional observations from in-situ and satellite sensors and remote sensing. Standardisation protocols and model intercomparison simulations will be made for the study as a whole (Figure 8). The sensitivity of models and their ability to reproduce surface to lower troposphere variation in measured carbonaceous aerosol concentrations will be evaluated. Model intercomparison will be done to identify bias and uncertainty in model processes.

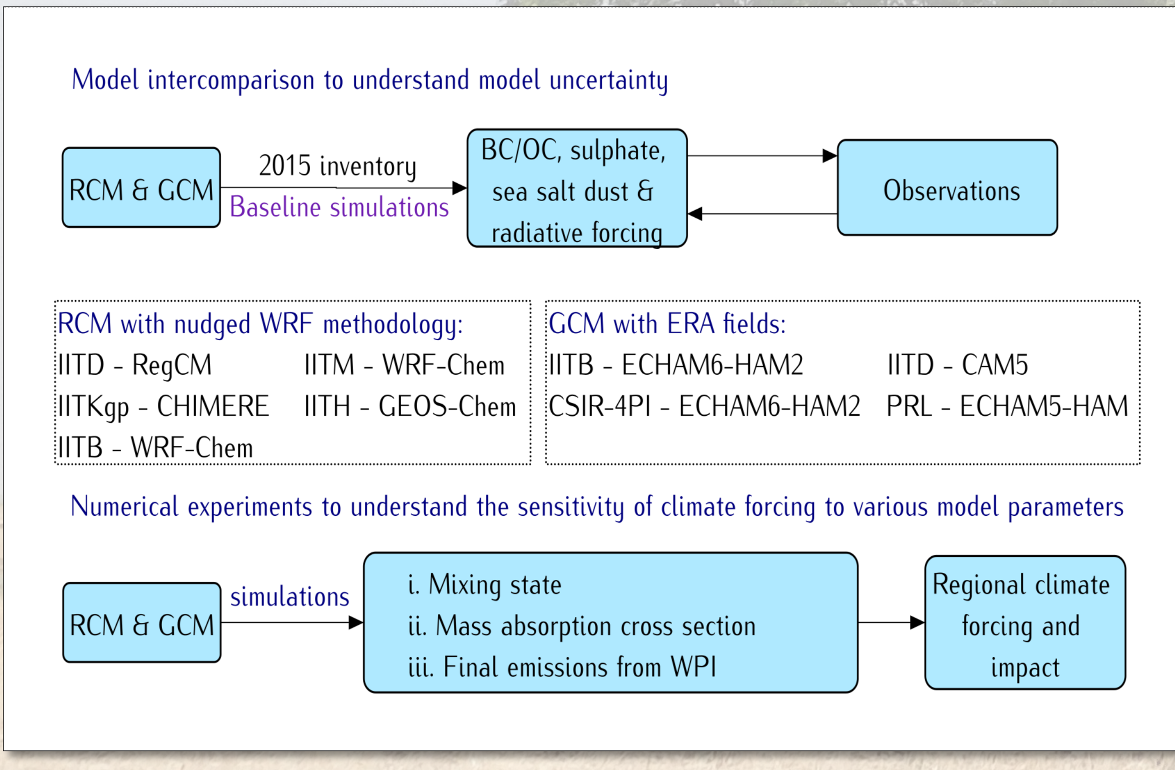

Figure 8. Identification of the atmospheric abundance and impacts of carbonaceous aerosols.

Regional chemical transport models (Figure 8) will use nudged WRF meteorology, with different chemical transport schemes. Models to be used include CHIMERE, coupled WRF-Chem, RegCM, and GEOS-Chem, with a spatial resolution of about 25 to 30 km grid size. All the regional models include all major aerosol species, BC, OC, dust, sea salt, $PM_{2.5}$, SO_2, and sulphate. Chemical transport models will be used to identify source contributions to carbonaceous aerosols and transport pathways which bring pollutants to sensitive ecosystems, particularly the Himalaya.

Deposition of carbonaceous aerosols in different regions would be calculated. Direct and indirect effect of aerosols on radiation will be studied using regional climate models, WRF-Chem and RegCM, with full meteorology-chemistry coupling. Models typically permit use of different meteorological parameterizations, different gas-phase chemistry schemes, and secondary organic aerosol modules. Different modules would be evaluated and compared using same emissions and meteorology.

Global models (Figure 8) that will be used are ECHAM6-HAM2 and CAM5-MAM3 at spatial resolutions of 180 x 180 km and 100 x 100 km, respectively. Model simulations will be made to understand source influence (Figure 9) and to address special hypotheses including separation of fast and slow responses and the effects of aerosols and land-use processes on monsoon rainfall.

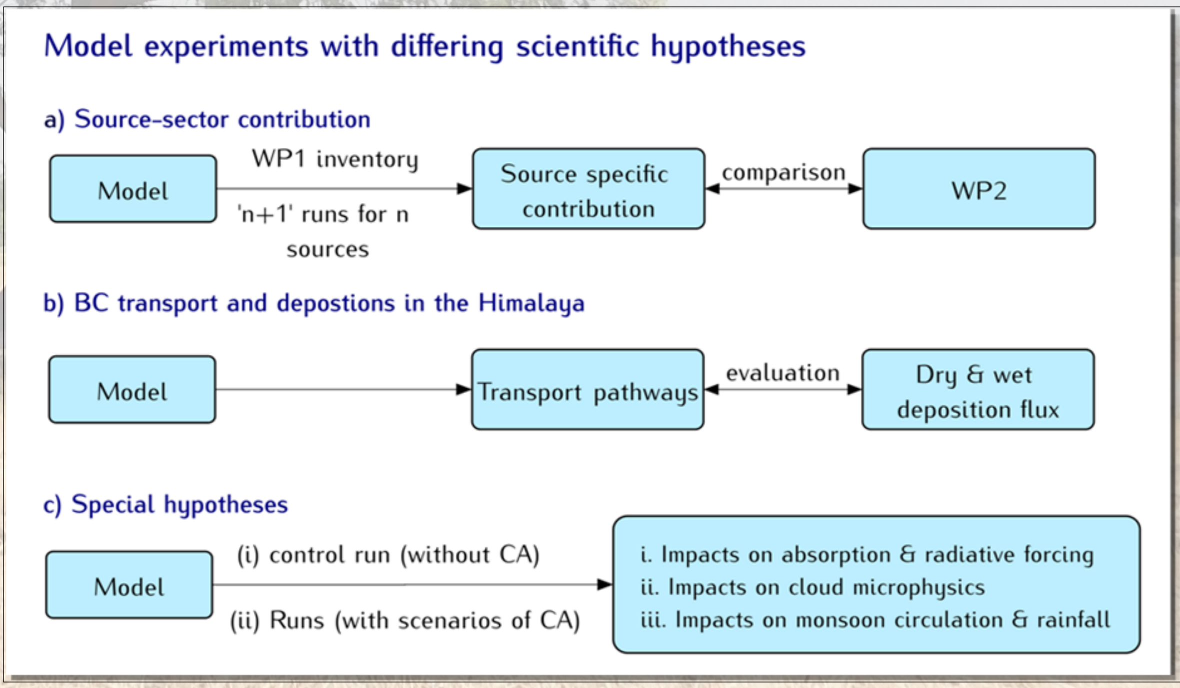

Figure 9. Special hypotheses on climate effects of carbonaceous aerosols.

4. Integration of Output and Data Centre

Work-flow and data transfer among the work packets would be made in a planned manner to lead to an integrated output (Figure 10).

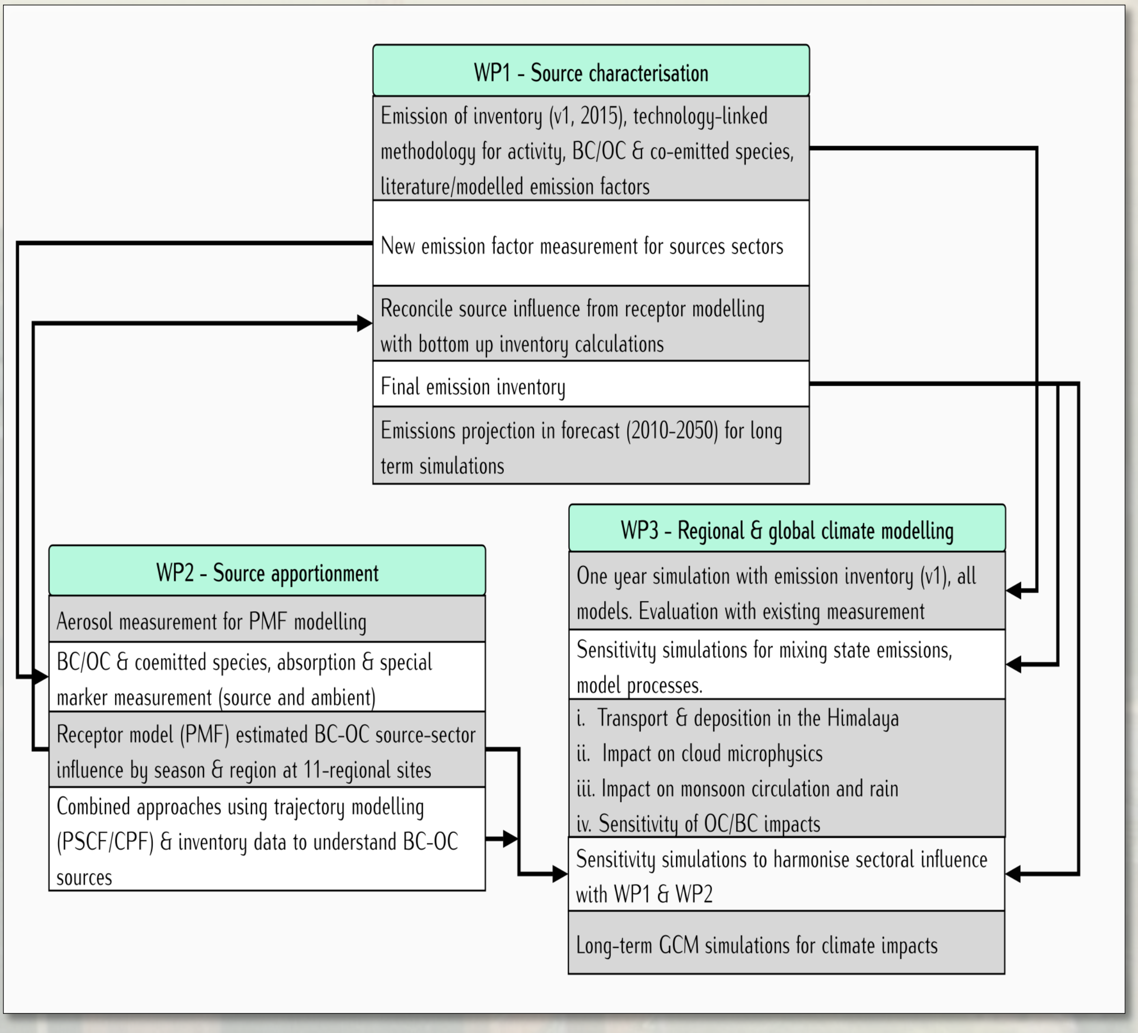

Figure 10. Work packet outcomes and links.

Emission factor measurements will be taken up in WP1, with the chemical characterisation of source sample filters carried out in WP2. These would be used in WP1 for conversion into quantitative emission factors for building a Tier II/Tier III emission inventory of carbonaceous aerosols and co-emitted species.

Regional source apportionment field sites will be run in WP2, for input to multivariate source apportionment modelling. Measurements from WP2 will be shared with WP3 for evaluation of the different chemical transport model simulations, made with the emissions inventory input, developed by WP1.

Source-tagged chemical transport simulations will be made by WP3. Harmonisation of quantitative source influence through top-down (multivariate receptor modelling) and bottom-up (chemical transport modelling) approaches will be done, between WP2 and WP3 at the sites, to constrain sectoral emission magnitudes and uncertainties in the emission inventory. Different base-years of the emission inventory will be deployed in regional climate models to predict atmospheric abundance, deposition, and climate effects of carbonaceous aerosols.

A data portal for sharing of data amongst the project investigators and a public website are envisaged (Figure 11), containing non-confidential information, such as a description of the project and consortium partners, regular information on progress and downloadable versions (when permitted by copyright) of any publication or literature generated through the project.

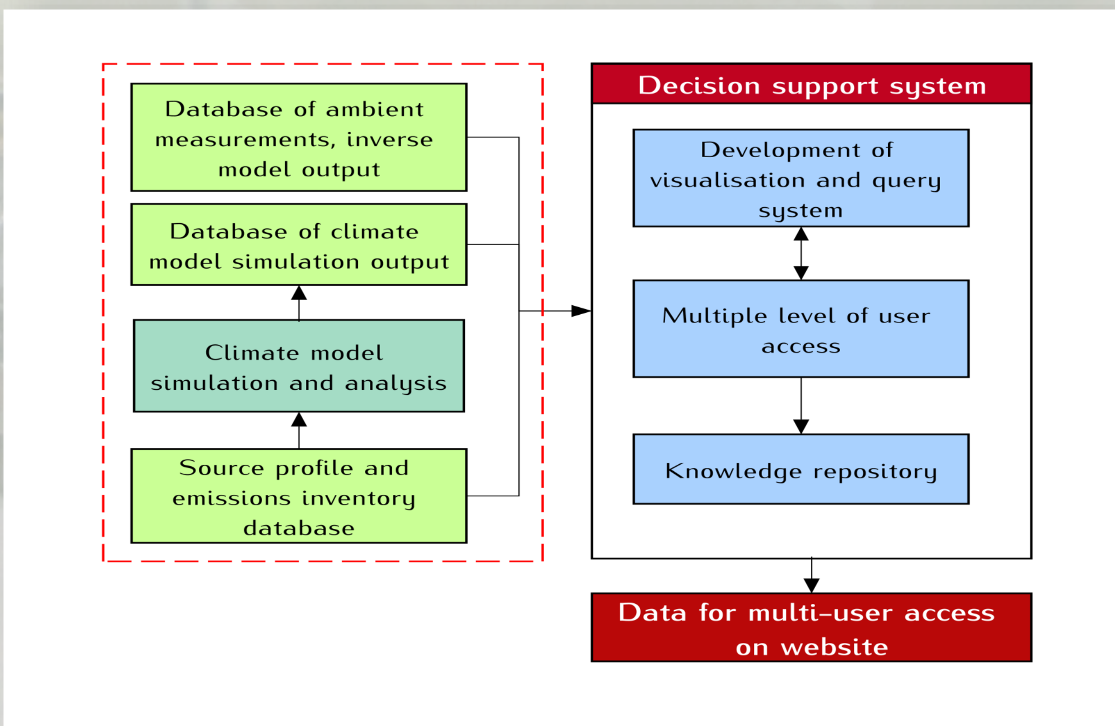

Figure 11. Data centre for archive and distribution.

5. Implementation Design and Coordination

The NCAP-COALESCE project management will be organised around a three-tier structure involving 17 institutions. This will include a Lead Institution, 8 Associate institutions and 8 PMF/inventory development institutions (figure 12).

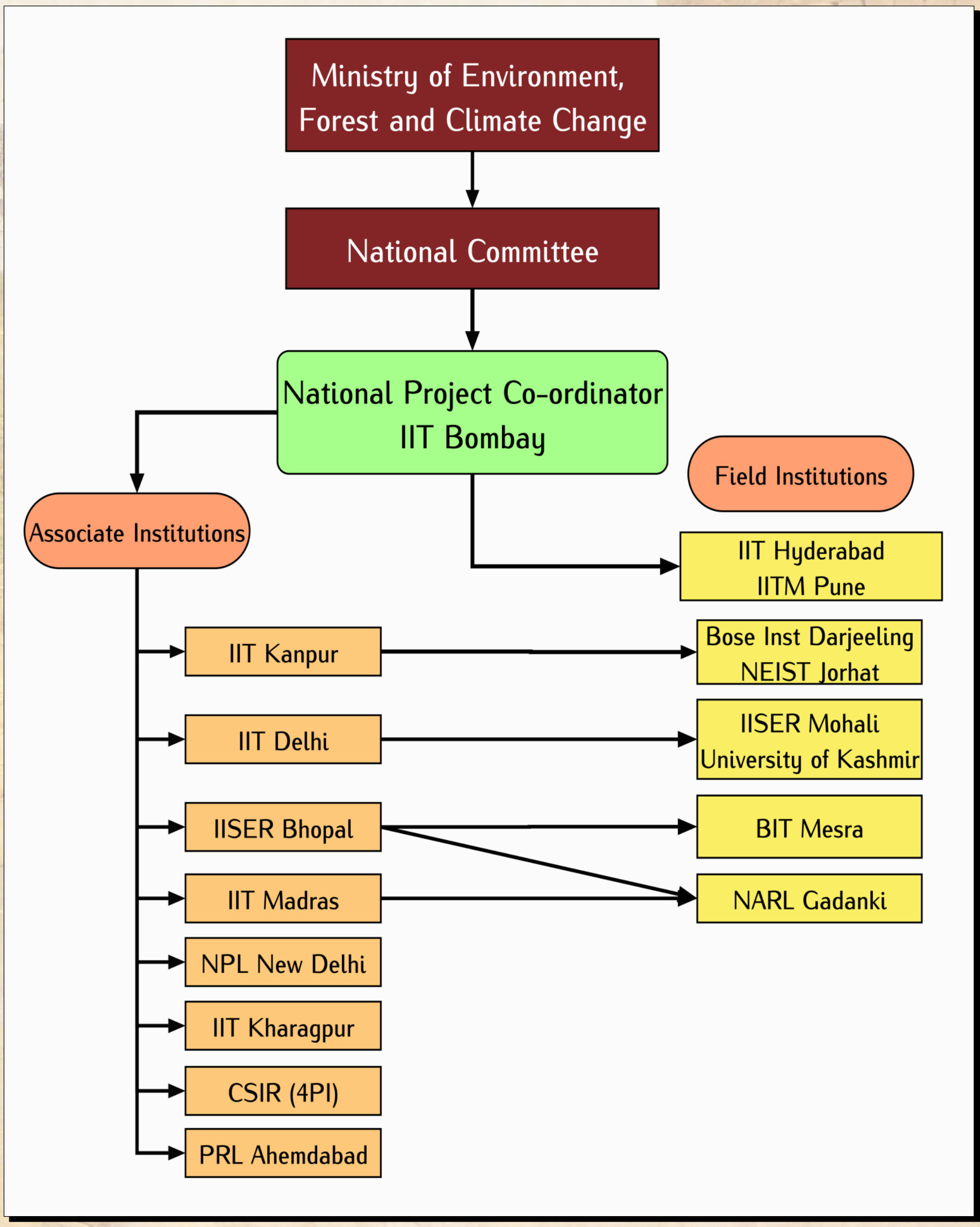

Figure 12. The NCAP–COALESCE project management structure.

A multi-pronged approach will be adopted towards building scientific capacity, by training M.Sc., M.Tech. and PhD students, as well as the creation of infrastructure and systems (for measurements and modelling) at participating institutions.

The primary role of field institutions is to support field stations for inputs to source apportionment modelling and for undertaking survey studies for activity data for building the emissions inventory. The Lead and Associate Institutions will coordinate and implement database development for emissions estimation, development and implementation of the protocols for aerosol sampling and chemical fingerprinting of emission source and regional background samples, multivariate source apportionment modelling and modelling regional chemical transport and climate impact. Documentation of best practices will be undertaken. Teaching and research modules will be prepared. Training of students will be undertaken at all the institutions which offer post-graduate programmes. Efforts will be made towards collaborative supervision and co-guidance of students to disseminate best research practices and produce integrated research output.

Research activities in the NCAP-COALESCE project should lead to significant advances in our understanding of key areas within carbonaceous aerosol influence on climate change. The dissemination of research findings and knowledge products such as models and decision-making tools will form an important part of the project activities.

Dissemination of findings to the scientific and government communities will be ensured through different channels including (i) a website, (ii) peer-reviewed publications, (iii) reports or publications on specific elements and outcomes. Over a period of time, the NCAP-COALESCE project would emerge as an important knowledge and information resource to support national and state actions responding to climate change caused by carbonaceous aerosols.

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