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Indian Network Project on Carbonaceous Aerosol Emissions, Source Apportionment and Climate Impacts (COALESCE)

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ABSTRACT: Climate change and air pollution have important societal consequences, especially in emerging economies, wherein transitions from polluting technologies to cleaner alternatives coincide with high population vulnerability to environmental threats. India is home to a fifth of the world's population and a gamut of human activities, employing a far ranging spectrum of technologies and fuels, with consequent emissions. Atmospheric fine particles or aerosols in the region predominate in carbonaceous constituents and dust. Multi-institutional studies in the region have earlier focused on natural and anthropogenic climate forcing by aerosols and feedbacks on regional and global climate. Important gaps remain in understanding human activities influencing emissions, emission aerosol properties, and regional atmospheric processes, specifically those related to carbonaceous aerosol impacts on climate and air quality. With an aim to address these gaps, the COALESCE (Carbonaceous Aerosol Emissions, Source Apportionment and Climate Impacts) project was launched on 7 July 2017. The project adopts integration of scientific methods developed by both the climate and air quality research communities. New fundamental knowledge from the project and strong links to India's policy framework would enable climate and clean-air action in the region. The article describes the scientific rationale, objectives, and planned activities under COALESCE to explore engagement with the international climate and air quality research communities and to enable eventual dissemination of research findings, knowledge products, and decision-support tools.

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Large-scale environmental challenges, like climate change and air quality degradation, govern the transformation of ecosystems, populations, and livelihoods. Human activities, which influence and alter the composition of the atmosphere, affect climate change and air quality. The Paris Agreement on Climate Change, which came into force in November 2016, following ratification by over 50 world nations, aims for a global response to limit global mean temperature increases above preindustrial levels to well below 2°C by 2100 while pursuing efforts to further limit the increase to below 1.5°C (United Nations Framework Convention on Climate Change; UNFCCC 2015). Recent evidence suggests that, under emissions consistent with current Nationally Determined Contribution (NDC) pledges, global warming could surpass the 1.5°C target (IPCC 2019). Thus, it is necessary to expand the focus of climate action, from a greenhouse gas (GHG)-only lens, to include agents that provide potential benefits to both climate and sustainable development.

Short-lived climate pollutants (SLCPs) exert a warming influence on climate and include particulate black carbon (BC), gaseous methane (CH_4), and tropospheric ozone (O_3), and some hydrofluorocarbons (CCAC 2014; UNEP and WMO 2011; UNFCCC 2015). Black carbon has an important role on the climate system, as it absorbs solar radiation, influences cloud processes, and alters the melting of snow and ice cover (Bond et al. 2013). Another light-absorbing type of carbonaceous aerosol is brown carbon (BrC; Laskin et al. 2015; Feng et al. 2013). SLCPs also impact air pollution, thus affecting public health and crop damage (Shindell et al. 2012; UNFCCC 2018). Specific to India, warming SLCP emissions arise from sectors and economic activities *unrelated* to those governing GHG emissions (Venkataraman et al. 2016), thus motivating additional and distinct attention to SLCPs, including carbonaceous aerosols. In the past two decades, a number of ground-based networks, field campaigns, and satellite observations have helped further our understanding of the characteristics and climate effects of aerosols in the Indian region. Earlier studies related to this region have focused on natural and anthropogenic climate forcing by aerosols, through direct radiative forcing and cloud microphysical effects, along with feedbacks on regional and global climate (Ramanathan et al. 2001; Moorthy et al. 2009; Lau et al. 2008).

Concerns related to climate change impacts of anthropogenic pollutants on multiple geographical scales led to the establishment of the Indian Network for Climate Change Assessment (INCCA; MoEF 2009) and the launch of the National Carbonaceous Aerosols Programme (NCAP; MoEF 2011). To identify important gaps related to carbonaceous aerosols, a consultative process under the auspices of the Indian Ministry of Environment, Forests and Climate Change, led to a series of scientific workshops and interministerial consultative meetings. The process of consultation culminated in the launch of a 5-yr (2017–22) multi-institutional research and capacity building initiative, Carbonaceous Aerosol Emissions, Source Apportionment and Climate Impacts (COALESCE), on 7 July 2017 to address *scientific complexities related to carbonaceous aerosols, focusing on issues underlying their origin and fate, and their role as drivers of regional climate change, over India*. The acronym COALESCE is serendipitous;

it signifies coming together, in both contexts of aerosol interparticle dynamics and an intermingling of diverse scientific expertise from a geographically widespread network of institutions. The COALESCE project has been envisaged as a major effort contributing toward building an integrated aerosol, air pollution, and climate research community in the South Asian geographical domain. The article describes the scientific rationale, objectives, and planned activities under COALESCE to explore engagement with the international climate and air quality research communities and to enable eventual dissemination of research findings, knowledge products, and decision-support tools.

The scientific rationale

Important gaps remain in understanding human activities influencing emissions, aerosol thermodynamic and optical properties, and atmospheric processes, specifically those related to carbonaceous aerosol impacts on climate and air quality. The climate and air quality research communities use two broad approaches: (i) development and deployment of detailed emission inventories in regional or global climate models and (ii) exploiting ambient chemical and optical measurements of $PM_{2.5}$ (mass concentration of particles with diameter smaller than 2.5 μm), in conjunction with meteorological variables, in receptor modeling tools. The present project aims to generate new knowledge related to reducing uncertainties linked to human activities influencing emissions, generating field measurements on source aerosol properties (microphysical, optical, and thermodynamic), measuring field emission factors, and improving our understanding of climate model processes influencing the aerosol life cycle. We review common scientific questions on carbonaceous aerosols faced by international climate and air quality communities, which motivate this network project.

Aerosol abundances and impacts. Many challenges remain in accurate understanding of aerosol abundances and impacts on regional and global scales. One of the key uncertainties in climate projections stems from the inadequate representation of aerosol processes and their interaction with clouds and precipitation in the regional climate models (RCMs) and global climate models (GCMs; Schiermeier 2010). For example, most models used in phase 5 of the Coupled Model Intercomparison Project (CMIP5; Taylor et al. 2012) fail to capture the observed distribution of aerosol optical depth (AOD) over the Indian subcontinent (Sanap et al. 2014). Simulated concentrations of both $PM_{2.5}$ and chemical constituents, including black carbon, are significantly lower than measurements in the Indian region (Pan et al. 2015; Bond et al. 2013), in terms of surface concentrations and absorption AOD. Possible causes cited for these underestimations include low bias in boundary layer relative humidity (RH), thus suppressing aerosol hygroscopic growth and formation of secondary inorganic aerosol, including nitrate (Pan et al. 2015). Simulations made using a detailed regional emission inventory (Venkataraman et al. 2018; David et al. 2018) continue to estimate too low aerosol abundance, prompting an evaluation of model processes that relate to the aerosol life cycle.

Aerosol radiative forcing and consequent reduction of ground-reaching solar radiation is well recognized (Satheesh and Ramanathan 2000; Padma Kumari et al. 2007). Krishnan and Ramanathan (2002) showed a dry season (winter and premonsoon) cooling, consistent with enhanced absorbing aerosol abundance, suggesting possible surface warming at regions nonlocal to the aerosol haze to balance local cooling. Significant atmospheric abundance of absorbing aerosols persists in the premonsoon season over India, whose influence on redistribution of solar energy and atmospheric heating on regional scales is not well understood.

Anthropogenic aerosol radiative forcing has been linked to declining trends in monsoon precipitation, in the Northern Hemisphere in general (Polson et al. 2014) and in South Asia in particular (Ramanathan et al. 2005; Bollasina et al. 2011; Ganguly et al. 2012; Salzmann et al. 2014; Krishnan et al. 2016; Guo et al. 2016). However, significant uncertainty persists in the ability of models to capture precipitation response to the different components, that is, direct and indirect, of aerosol radiative forcing and to specific effects of carbonaceous aerosol species. We need to better understand the interplay between the large-scale interhemispheric energy balance change largely linked to scattering aerosols like sulfates and the positive accommodation of convection on daily to monthly time scales, to radiative effects of absorbing aerosols like black carbon (Lau et al. 2006; Vinoj et al. 2014). Studies suggest that observed drying rainfall trends over South Asia during 1950–2000 are captured in CMIP5 models, including either component of aerosol radiative forcing (Salzmann et al. 2014), while others (Guo et al. 2015) suggest that the indirect forcing component is crucial. Importantly, there is a need to understand monsoon response to indirect effects of aerosols, and to decoupling of different forcing elements. Further, climate change can influence air quality through anomalous heating and circulation patterns on regional scales. This can feed back to alter mesoscale meteorology and affect the formation and abundance of air pollutants (Racherla and Adams 2006), worsening $PM_{2.5}$ levels and the severity and frequency of high-ozone events or "episodes." Such effects are so far not understood in the Indian region.

Aerosol emissions and atmospheric processes. Emission biases in modeling studies over South Asia arise primarily from too low emission magnitudes from agricultural residue burning and biomass fuel usage in the emission inventories (Pan et al. 2015). There are significant uncertainties in the estimation of carbonaceous aerosol emissions from India, reflected in 2–3 times different emission magnitudes among global (Klimont et al. 2017; Ohara et al. 2007; Borken et al. 2007; Zhang et al. 2009) and regional emission inventories (Jaiprakash and Habib 2018b; Sahu et al. 2008; Guttikunda and Mohan 2014; Sadavarte and Venkataraman 2014; Paliwal et al. 2016). The disagreement among global inventories for India has been attributed primarily to the use of uncertain emission factors (grams of pollutant emitted per kilograms of fuel burned), from severe paucity of regional measurements (Venkataraman et al. 2005; Weyant et al. 2014), reflecting field conditions of actual use.

Central to air pollution mitigation is an understanding of quantitative source contributions to ambient air pollution. A quantitative understanding of the origin and sources of $PM_{2.5}$, and its chemical constituents including carbonaceous aerosols, requires exploiting ambient measurements (chemical and optical) of fine particulate matter ($PM_{2.5}$ or mass concentration of particles with diameter smaller than 2.5 μm) in conjunction with meteorological variables, in receptor models, like the chemical mass balance (Friedlander 1973; Watson 1984) and positive matrix factorization (Paatero 1997) models. Exploiting the power of receptor models requires basic measurement of detailed aerosol chemical composition data (~25 species or more), enhanced by that of organic molecular markers (Schauer and Cass 2000), ratios of target chemical compounds including isotope ratios (Gustafsson et al. 2009; Guazzotti et al. 2003), and a clear accounting of secondary particles (both organic and inorganic; Viana et al. 2008; Singh et al. 2016; Lee et al. 2007). Recently, factor analytic modeling has been applied to Indian datasets for both regional (Bhanuprasad et al. 2008; Mehta et al. 2009; Cherian et al. 2010; Prakash et al. 2018) and urban (Baxla et al. 2009; Roy et al. 2009; Chakraborty and Gupta 2010; Sunder Raman and Ramachandran 2010; Sunder Raman et al. 2010; Habib et al. 2010; Rajput et al. 2016; Chakraborty et al. 2017) studies. However, available studies in the Indian region cite measurement of too few samples and chemical species, lack of components like thermal optical carbon fractions, organic molecular markers, isotope markers of carbon, and other inorganic species, essential to resolve similar sources.

In terms of atmospheric transformations of carbonaceous aerosols, significant gaps relate to atmospheric processes that influence abundances and optical properties of secondary organic aerosols (SOA) and brown carbon (BrC). Atmospheric SOA arises both from oxidation of biogenic precursors like isoprene and from volatile organic compounds emitted by biomass burning or other anthropogenic sources (Shrivastava et al. 2017). A significant fraction of SOA, termed BrC, is radiation absorbing in ultraviolet–visible wavelength region (Laskin et al. 2015) and could significantly amplify atmospheric absorption leading to a positive radiative forcing (Feng et al. 2013). Limited studies in the Indian region have detected SOA, including water soluble organics in fog (Kaul et al. 2011) and molecular markers of SOA (Fu et al. 2016) in urban areas. Significant absorbance of water soluble organic carbon (Choudhary et al. 2017) and links of BrC to both biomass burning and secondary aerosol of biogenic origin (Kirillova et al. 2014; Chakrabarty et al. 2014) are beginning to emerge in the Indian region. However, the very limited understanding of secondary organic aerosol points to an urgent need for coordinated regional-scale measurements and modeling initiatives to better understand SOA and BrC formation and their spectral optical properties.

International significance. In terms of international significance, it is envisaged that the COALESCE project would provide new knowledge, useful to the global climate and air quality communities. As discussed in the following sections, ground-truthing existing inventory methodologies through field surveys to estimate presently assumed coefficients (including residential biomass fuel mix, extent of use of secondary biomass fuel, fraction of agricultural biomass burned in field, biomass density in fields, extent of use of different fuels and kiln technologies in brick production, fraction of superemitting vehicles) would reduce uncertainties in emission estimates. Improved emission inventory methodologies (e.g., for the brick production sector), as well as a significantly improved emission inventory for India, would be generated for possible integration into global emission inventories for climate and air quality modeling. Comprehensive field measurements of aerosol emission factors and speciated source profiles (organic molecular markers, C-isotope ratios, brown carbon) for sources with scant measurements worldwide, planned in this study, would be useful to the air quality community for use in receptor modeling for source identification. An extended observation phase of 2 years, at 11 pan-India sites, would provide alternate-day, fully chemically speciated measurements of $PM_{2.5}$, useful for model evaluation and satellite algorithm development. We expect to explore extended receptor modeling methods and develop related heuristics. The atmospheric modeling exercises include a suite of RCMs and GCMs, which are widely used by the global community for regional and global climate modeling. A planned model intercomparison experiment would help further our understanding of model deficiencies and possible bias in physical and chemical process parameterizations, particularly over tropical regions. International partnerships are being explored by COALESCE investigators to enhance observation capability and widen hypotheses, toward furthering our understanding of aerosol processes, properties, transformations, and impacts.

Objectives

Furthering an understanding of carbonaceous aerosols regional impacts thus requires a multiscale integration of field measurements with multiple modeling methods. The COALESCE project (https://ncapcoalesce.iitb.ac.in/) is envisaged as a framework, which incorporates a multidisciplinary scientific approach, joint research and training, and strong links to policymaking, to coordinate scientific efforts in the Indian geographical domain. The COALESCE project would help achieve the following scientific objectives and related specific scientific problems (Table 1):

- Reduce current uncertainty in emission magnitudes of carbonaceous aerosols (and copollutants) from different source categories from India.
- Identify and quantify sources influencing abundance and properties (chemical and optical) of aerosols, specifically carbonaceous constituents, on regional scales.

- Estimate the impact of aerosols, specifically carbonaceous constituents, on climate variables, along with climate feedback on air quality, through regional- and global-scale models.
- Evaluate secondary aerosol formation, organic aerosol source resolution (impacts on air quality), and estimate brown carbon absorption (impacts on climate).

The project will attempt scientific capacity building through the following mechanisms:

Adoption of a multipronged approach toward building scientific capacity, through training of students and research staff as multidisciplinary scientists.

- Creation of infrastructure and systems, for measurements and modeling, at participating institutions.
- Adoption of standard scientific protocols and data formats consistent with international standards.
- Dissemination of research findings, knowledge products, and decision-making tools.

Table 1. Key objectives and specific scientific problems of COALESCE.

Key objectives	Specific scientific problems
1) Reduce current uncertainty in the magnitude and sectoral distribution of carbonaceous aerosols (and copollutant) emissions over India	(i) Measurement of field emission factors of carbonaceous aerosol fractions [black carbon (BC), organic carbon (OC), and brown carbon (BrC)], speciated $PM_{2.5}$ and selected co-emitted gases from major sources of regional importance (i.e., residential cooking, space heating, water heating and lighting, brick kilns, on-road diesel transport, and agricultural residue burning).
	(ii) Understanding the influence of technology, operating practice, and fuel properties on microphysical, chemical, and optical properties of aerosol emissions under field conditions.
	(iii) Identification of sources that emit the darkest (net warming) particles, through measurement of spectral mass absorption and scattering cross-section, chemical, and microphysical properties.
	(iv) Estimation of activity rates in the use of different fuels, technologies, and practices in key carbonaceous aerosol emitting sectors over India.
	(v) Development of a gridded carbonaceous aerosol emission inventory for India, with improved sectoral methodologies from ground-truthing and validation with field survey data.
2) Identify and quantify sources influencing abundance and properties (chemical and optical) of anthropogenic aerosols and carbonaceous constituents over India	(i) Seasonal and spatial variation in aerosol chemical composition and optical properties at 11 regionally representative sites across India.
	(ii) Evaluate predominance of SOA and BrC in regional aerosols and understand atmospheric processes influencing them.
	(iii) Quantitative source apportionment of $PM_{2.5}$ and carbonaceous aerosols and identification of sources and geographical regions influencing high pollution episodes. Distinguishing similar sources of carbonaceous aerosol emissions using chemical fingerprinting (organic molecular markers, thermally resolved carbon fractions and C-isotopes).
	(iv) Source apportionment of aerosol optical properties and resolution of primary vs secondary sources of aerosols using multilinear extended models.
	(v) To quantify source-sector influence on $PM_{2.5}$ and carbonaceous aerosol abundance, through quantitative comparison of RCM predictions with PMF receptor modeling by season and region.
3) Estimate the impact of aerosols (anthropogenic and carbonaceous) on regional climate variables, along with climate feedback on air quality	(i) Multimodel ensemble simulations, with RCMs and GCMs, for evaluation of model diversity in annual and seasonal anthropogenic aerosol variables and aerosol processes, including mass and species concentrations, sulfate formation (SO_2/SO_4 ratios), dry and wet deposition, total and species AOD, SSA, asymmetry parameter and radiative forcing.
	(ii) Estimating aerosol radiative forcing over India and the contribution of carbonaceous aerosols, resolved by source, season, and region.
	(iii) Estimating the response of South Asian monsoon precipitation response to radiative forcing of aerosol direct, indirect, and total effects.
	(iv) Special hypotheses including - sensitivity of radiative forcing to changes in emissions, mixing state, and aerosol optical properties (mass absorption cross section). - carbonaceous aerosol influence on temperature response and frequency of high temperature extremes. - influence of anthropogenic aerosols on circulation patterns and cloud microphysics. - trends in aerosol deposition and radiative forcing, temperature, and snow cover in the Himalaya.

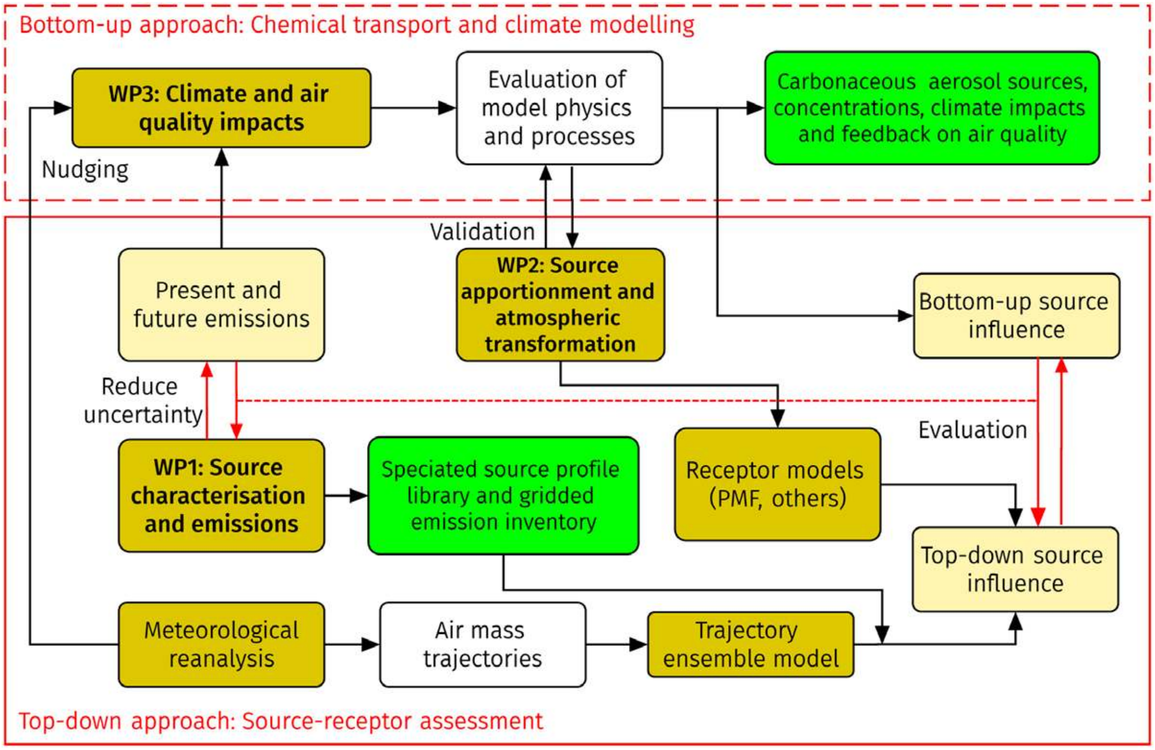

Fig. 1. COALESCE project concept combining top-down and bottom-up approaches, interlinking emissions, source apportionment and atmospheric transformation, and climate and air quality impacts.

The COALESCE project concept integrates "bottom-up" approaches or emissions-driven climate modeling, with "top-down" methods or source apportionment through multivariate modeling using in situ measurements (Fig. 1). Bottom-up approaches would provide an evaluation of the carbonaceous aerosol life cycle, atmospheric transport, sinks and chemical conversion, and modeled aerosol influence on climate variables like the radiation balance, temperature, and rainfall, through multimodel ensemble simulations using a suite of regional and global models. Top-down approaches will use in situ measurements from a regional observational network of detailed aerosol chemical composition specific markers, satellite data, and trajectory ensembles for quantitative source apportionment of $PM_{2.5}$ and carbonaceous aerosol concentrations through receptor modeling and to understand effects of aerosol aging on their chemical and optical properties. A harmonization of source influence estimated by bottom-up and top-down approaches would reduce uncertainties in the emission inventory. The strongly interlinked research objectives are organized as three distinct work packages, described below.

Work package 1: Source characterization and emissions. An evaluation of recent emission inventory methodologies (Venkataraman et al. 2018; Pandey and Venkataraman 2014; Sadavarte and Venkataraman 2014) identified uncertain assumptions and missing information for the four most dominant sources of carbonaceous aerosol emissions, that is, residential sources (biomass cooking, water and space heating, lighting), agricultural residue burning, fired-clay brick production, and on-road transport, particularly using diesel fuel. In the past 18 months since the launch of the project, a national-scale survey study has been designed and is currently ongoing at 14 COALESCE institutions (Figs. 2a,b), using adaptations of published survey methodologies (see "Details of survey methodology and locations" and Table ES3 in the supplement). We use an integration of field surveys for fuel use estimation, field measurements from emission sources, and measurement of emission aerosol properties to obtain emission factors, speciated source profiles, and an emission inventory (Fig. 3). Selection of cities for vehicle surveys reflects city classification by tier (RBI 2011) and vehicle classification (Table ES2; MoRTH 2018). Statistical methods are used for random selection of households and agriculturists, ensuring representativeness at village levels to avoid similarity and exclude outliers. To ensure socioeconomic representation, several among the 115 districts classified as developmentally backward districts in India are included in surveys (Tables ES2 and ES3).

Field measurements of emission factors are being made, using a portable source sampler adapted from previous work (Jaiprakash et al. 2016; Jaiprakash and Habib 2018a,b) (see "Details of field measurement campaigns," Fig. ES2, and Table ES4 in the supplement) using the carbon balance method and quantitative dilution calculations ("Details of field measurement campaigns," in the supplement). Real-time and time-integrated emission factors, as well as microphysical and optical properties of emission aerosol (Table ES4), will be measured during field campaigns in the dry season of 2020. Full chemical speciation of source emissions aerosol will be made toward developing a speciation source profile library. Data and measurements from the comprehensive field campaigns will be exploited in an energy-emissions modeling framework to develop a gridded emissions inventory for India at the highest possible tier of detail.

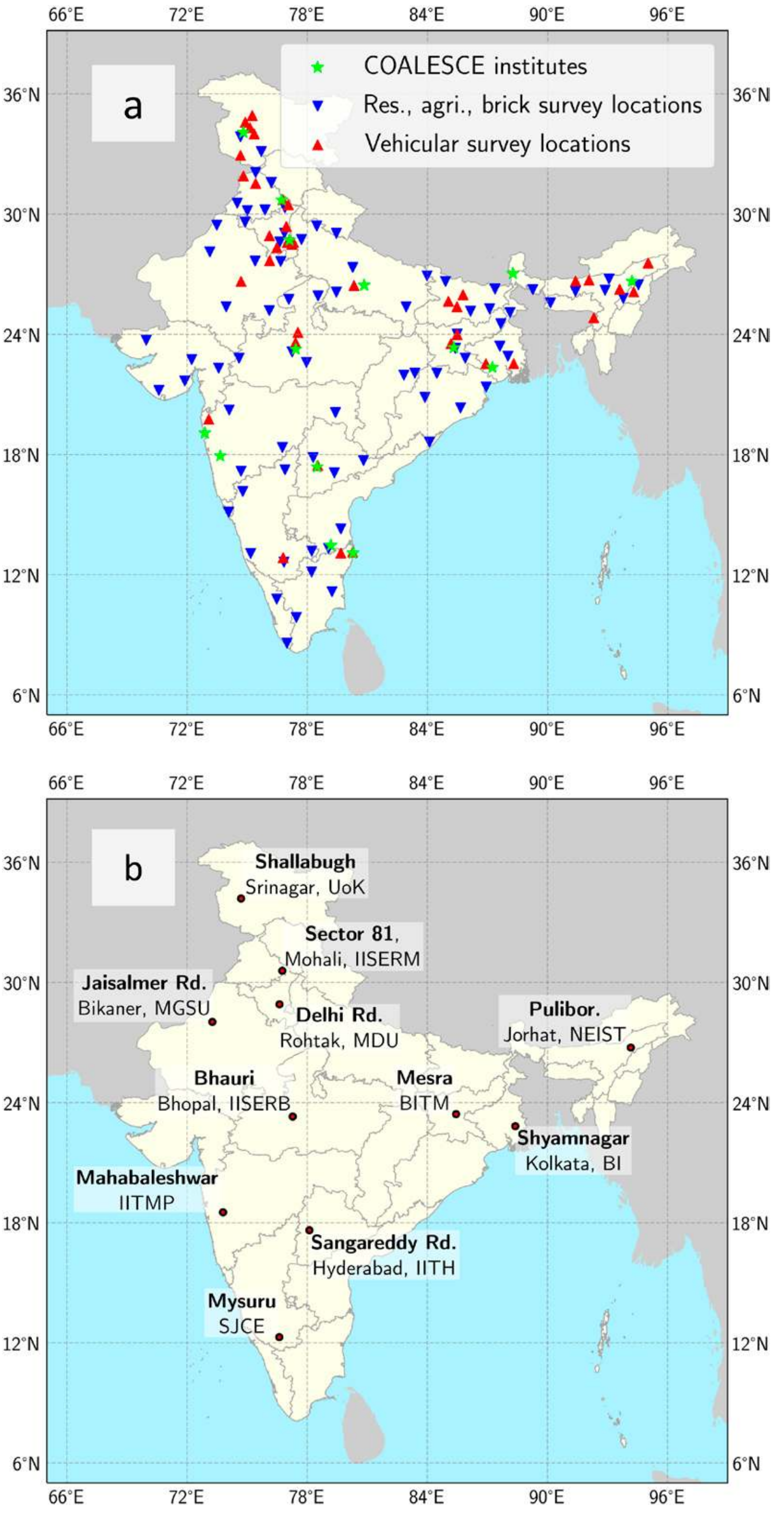

Fig. 2. (a) Districts and locations (list in Table ES3) for survey studies, a subset to be chosen for emission measurement studies. (b) Location of field sites in the regional observation network (list and details in Table ES2).

Work package 2: Source apportionment and atmospheric transformation. The main steps involved in identifying and quantifying major sources of carbonaceous aerosols through the integration of measurements with receptor approaches, along with adopted quality control and quality assurance methods, are summarized (Fig. 4; see "Details of participating GCMs and RCMs" and Table ES5 in the supplement). A chemically speciated $PM_{2.5}$ dataset, with measurements of 40–50 bulk chemical species, is being measured for an extended observational period (EOP; 2019–20) from 11 strategically chosen sampling sites across India (Fig. 2b). Site-selection

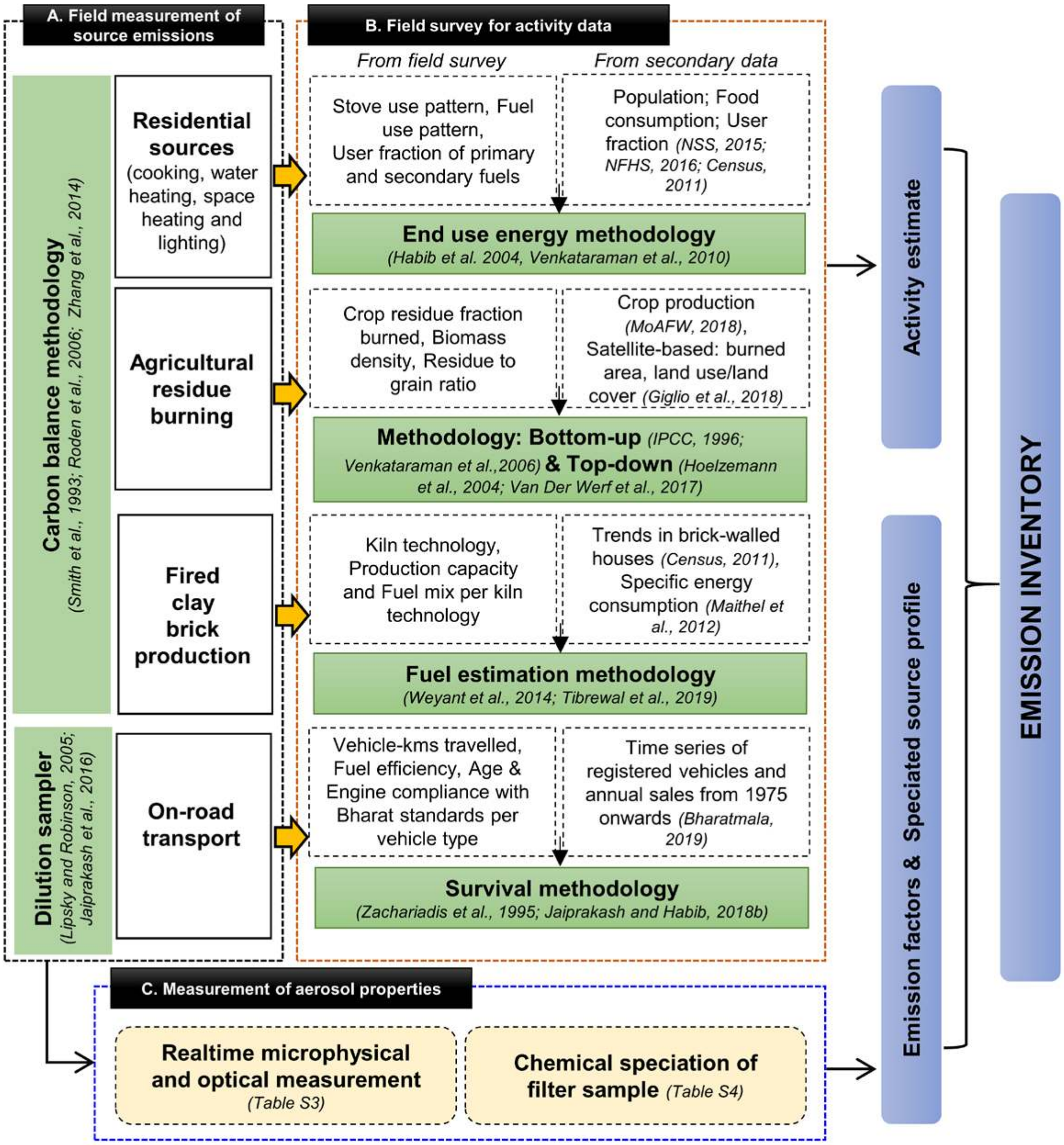

Fig. 3. Schematic of integration of field measurements from emission sources, surveys for fuel use estimation and measurement of emission aerosol properties to obtain emission factors, speciated source profiles, and an emission inventory.

criteria are modeled after large networked studies across the world, including the IMPROVE network (http://vista.cira.colostate.edu/Improve/wp-content/uploads/2016/04/SOP-126-Site-Selection.pdf). We will apply receptor modeling methods including positive matrix factorization (PMF) for deducing regional atmospheric abundance of carbonaceous aerosols (Fig. 4). Furthermore, measurements of molecular markers [with gas chromatography–mass spectrometry (GC-MS)] and stable carbon-isotope techniques will enhance the ability to distinguish similar sources of carbonaceous aerosol emissions (e.g., petrol from diesel; kerosene wick lamps from kerosene stoves, biofuel for energy from open burning of agricultural residue or forest biomass). Measurements to be made to resolve similar source types include, but are not limited to,

1) thermally fractionated organic and elemental carbon;
2) organic molecular markers, for example, levoglucosan, hopanes, and diacholastane;
3) carbon isotope analysis; and
4) key constituents of secondary organic aerosol and brown carbon.

These measurements will permit the application of standard PMF analysis as well as the multilinear engine-2 (ME-2) algorithm and rolling PMF analysis to thermally fractionated carbonaceous aerosol together with molecular markers, carbon isotopes, meteorological parameters, and auxiliary gaseous species measurements to enhance carbonaceous aerosol source resolution and to distinguish primary and secondary sources.

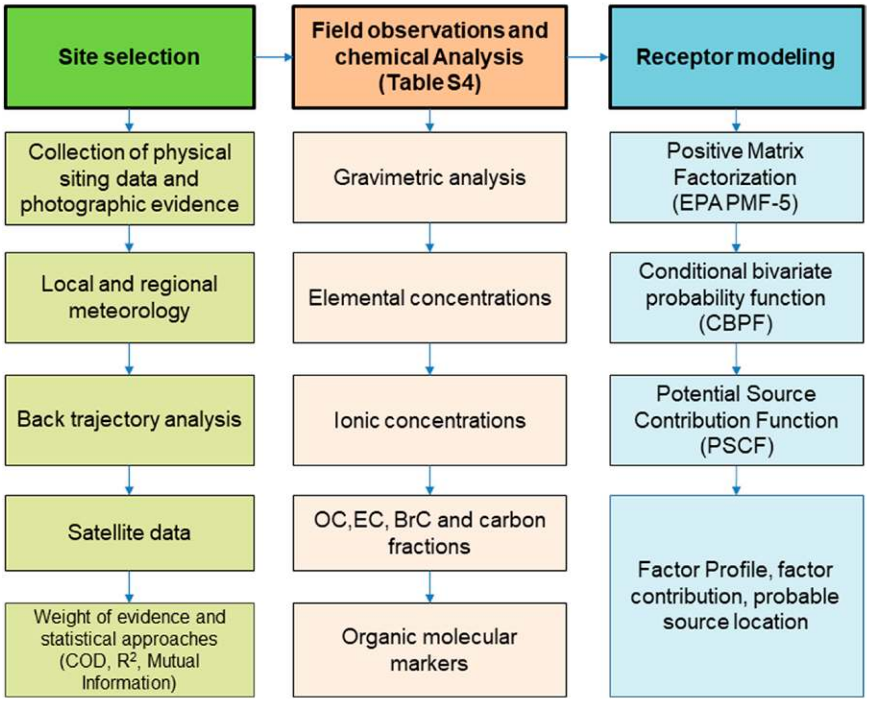

Fig. 4. Schematic of ambient measurements, chemical speciation, and receptor modeling for source apportionment.

Work package 3: Climate and air quality impacts. Modeling studies will play a crucial role in COALESCE to connect aerosol properties and processes to their impacts on climate variables and air quality. Participants and model description (physics options, schemes, and setup) for RCMs and GCMs are given in the supplement ("Details of participating GCMs and RCMs" and Tables ES6 and ES7). Work package 3 has two components, detailed in the following sections: (i) evaluation and intercomparison of models and (ii) special experiments to test hypotheses on aerosol–climate interaction and climate impacts on air quality.

Model intercomparison. As part of the model intercomparison exercise one set of simulations termed "free-run" has been made with each participating RCM and GCM predicting its own meteorology to drive the life cycle of aerosols and other chemical species. The purpose of carrying out the free-run was to evaluate the credibility of all participating RCMs and GCMs in simulating the seasonality of important meteorological variables and the magnitude of aerosol concentrations and AOD. Model performance will be addressed in "standard simulations" (Table 2), using identical emission inventory inputs and constrained meteorology. Standard simulations for RCMs (standard simulations I, Table 2) will be made for the year 2015, where the meteorological output is assimilated with observations every 12 h using the 3DVAR technique (Barker et al. 2012), keeping the chemical fields continuous across the 12-h segments (Fig. ES3). Standard simulations for GCMs for the period 2005–14 (standard simulations, II, Table 2) will be made using model meteorology nudged toward ERA-Interim reanalysis data. Selected meteorological variables, aerosol properties, and cloud properties (Table 2) from simulations will be evaluated against satellite, various reanalysis data products, and in situ and remote sensing observations (see Table ES8) from the Indian region as well as observations that are being made at COALESCE network stations.

Special experiments. Additional special experiments are planned to better understand processes that influence the life cycle of aerosols and their feedback to climate variables (special experiments I and II, Table 2). It is planned to quantify the radiative forcing due to aerosols and aerosol effects on clouds. Further, the response of the Indian monsoon system to changing emissions of aerosols will be evaluated. It is planned to carry out a series

Table 2. Simulation setup for model intercomparison and special experiments for RCMs and GCMs.

<table>
<tr><td rowspan="2">Standard simulations I (RCMs)</td><td>Simulation setup: 1-yr (2015) simulation with meteorology assimilated every 12 h using 3DVAR technique (Fig. ES3)</td></tr>
<tr><td>Initial and boundary conditions: ERA-Interim data for meteorological initial and boundary conditions; chemical initial and boundary conditions from MOZART or model default (LMDZ-INCA in WRF-CHEMERE and GEOS global in GEOS-Chem).</td></tr>
<tr><td rowspan="2">Standard simulations II (GCMs)</td><td>Simulation setup: 10-yr (2005–14) simulations with nudging with ERA-Interim data.</td></tr>
<tr><td>Initial and boundary conditions: SST and SIC boundary conditions for AGCMs are from HadISST_SST and HadISST_ICE, respectively.</td></tr>
<tr><td rowspan="2">Special experiments I (RCMs)</td><td>Simulation setup: 2-yr simulations (2019–20) by selected models with source-tagged emissions, that is, with new emission inventory (SMOG-India–COALESCE, under development).</td></tr>
<tr><td>Initial and boundary conditions: ERA-Interim data for meteorological initial and boundary conditions; chemical initial and boundary conditions from MOZART or model default (LMDZ-INCA in WRF-CHEMERE and GEOS global in GEOS-Chem).</td></tr>
<tr><td rowspan="2">Special experiments II (GCMs)</td><td>Simulation setup: Two sets of 30-yr (1985–2014) ensemble simulations (3 members) will be made by selected models, with (i) combined direct/semidirect and indirect aerosol forcing turned on, and (ii) direct/semidirect forcing component turned off.</td></tr>
<tr><td>Initial and boundary conditions: Model-based initial conditions with perturbation for generation of ensembles; SST and SIC boundary conditions for AGCMs for 1985–2014 from HadISST_SST and HadISST_ICE, respectively.</td></tr>
<tr><td colspan="2">Emissions:
• Sectoral emissions from energy, transport, industry, domestic, agricultural waste burning: Indian region from SMOG-India V1a (1985–2015; ncapcoalesce.iitb.ac.in) and rest of the world from CEDS (Community Emissions Data System; Hoesly et al. 2018). Emissions from urban fugitive dust: Indian region (www.urbanemissions.info) for 2015. Global emissions from shipping, solvents and agriculture (CEDS), wildfires (GFED-Global fire emissions database; Giglio et al. 2013), trash burning (Wiedinmyer et al. 2014), and ammonia (CEDS, Hoesly et al. 2018).
• Species used in the simulations: black carbon (BC), organic carbon (OC), sulphur dioxide (SO_2), nitrogen oxides (NO_x), ammonia (NH_3), non-methane volatile organic carbon (NMVOCs) (Sarkar et al. 2016) speciated to model chemical mechanism, mineral matter [$MM = PM_{2.5} - BC - OC \times (OM/OC\ ratio)$].
• Spatial resolution: 0.25° × 0.25° (RCMs) and 0.5° × 0.5° (GCMs); temporal resolution: monthly.</td></tr>
<tr><td colspan="2">Selected variables for intercomparison:
• <i>Meteorology:</i> 2-m temperature, 10-m winds, precipitation, surface pressure; relative humidity, wind vectors (u, v, ω) at all vertical levels.
• <i>Aerosols:</i> Surface concentrations, dry and wet deposition, columnar load, AOD, level-wise extinction, asymmetry parameter, and single scattering albedo; for the aerosol species SO_4, NO_3, NH_4, OC, BC, sea salt, dust, mineral matter. Emissions of dust, sea salt, biogenic NMVOCs, and dimethylsulfide (DMS).
• <i>Radiation:</i> Shortwave upwelling flux, clear sky and cloudy regions at surface and top of the atmosphere, outgoing long-wave radiation, net SW/LW flux at top of the atmosphere, radiative forcing for clear and cloudy conditions.
• <i>Clouds:</i> Cloud fraction (2D and 3D), cloud droplet effective radius, cloud drop number concentration, ice water path, liquid water path, ice effective radius, cloud optical depth, and cloud condensation nuclei.</td></tr>
</table>

of longer period (30 years) hindcast simulations (1985–2015) using selected GCMs and understand separately the effect of aerosol direct, semidirect, and indirect forcing on the rainfall distribution across India. In addition, specialized experiments will be carried out to understand the sensitivity of the aerosol radiative forcing to changes in aerosol emissions, mixing state and aerosol optical properties, and aerosol impacts on remote ecosystems like the Himalaya. Improving scientific understanding of RCMs will be attempted through simulation of aerosol fields and properties with (i) fully coupled chemistry and meteorology (WRF-Chem, WRF-CMAQ) versus an uncoupled mode (WRF-CHIMERE, GeOS-Chem, RegCM),

(ii) different chemical mechanisms and aerosol physics (WRF-Chem with RADM2/SORGAM-MADE modal scheme and CBMZ-MOSAIC sectional scheme), (iii) different meteorological data-assimilation cycles (12 and 48 h) affecting aerosol feedbacks, and (iv) a dynamic BC aging scheme (RegCM).

Data management system. The project website (https://ncapcoalesce.iitb.ac.in/) acts as the "public face" of the project for sharing project information on aims and objectives, partner details, research activities and highlights, events, and resources.

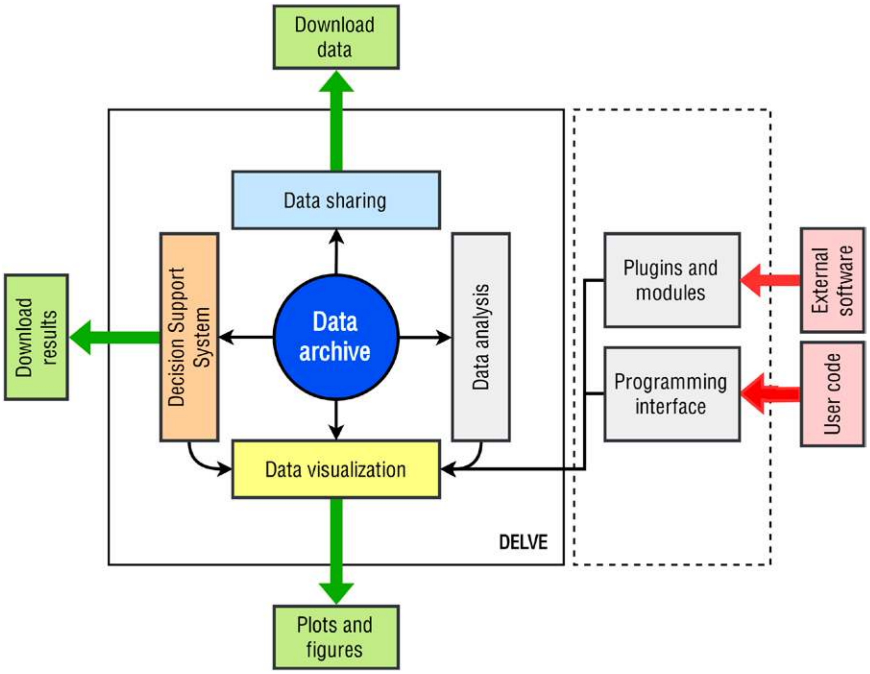

Fig. 5. Schematic of key features of the data portal, DELVE.

A data management system, DELVE (Data Exploration Analysis Visualization and Extraction System), is being developed as an integral component of this project, to cover practical data-sharing arrangements during the program and subsequent long-term availability of the datasets. DELVE is now hosted on the project web page and serves data sharing needs among the participant groups. DELVE will provide a variety of functionality related to data analysis, visualization, and extraction of data on demand, along with hosting an emission decision support system (Fig. 5). DELVE will serve the following functions: (i) a repository for datasets (both measurements as well as model simulations) generated in this project, (ii) a platform hosting data-analysis tools with functions like time series analysis, regression analysis, and multivariate analysis tools; and (iii) a platform on which data can be depicted as scatterplots, time series plots, pie charts, and bar graphs. An extensive data visualization module with basic 2D and 3D plotting capabilities, spatial plots (2D and 3D), and animated spatiotemporal plots will be part of DELVE. A programming interface on the data portal and links to some external software, through plugins and modules, will facilitate customized data analysis.

An emissions decision support system, for national emissions inventory data management and future emissions scenario generation, is under development as SMoG-India (Speciated Multi-Pollutant Generator–India). SMoG-India will enable display/visualization of the inventory using open-source GIS, provide tools for making policy decisions by comparing future scenarios with multiple impacts assessment, and will be hosted on DELVE. Periodic release of datasets to the research community would enable collaborative research. Our aim is to develop the COALESCE observational and modeling network to conform to standardized international practices and procedures, through the adoption of standard data formats and protocols and adhering to an open data policy.

Potential linkages with other programs

The COALESCE project has been envisaged as a major initiative bringing together the climate and air pollution research communities in India. Significant efforts are underway to explore engagement with the international research community. We are exploring engagement with initiatives listed below, while others are likely to emerge during project execution. Complementarities of these India region initiatives with COALESCE could include a joint intensive observational phase and exploring possible uses of aerosol chemical speciation data, a significantly improved emission inventory, and source apportioned PM information for collaborative studies.

Centre for Climate Change Research (CCCR), Indian Institute of Tropical Meteorology, Pune. The CCCR undertakes research to better understand the science of climate change over the tropics and enable improved assessments of the regional climate responses to global climate change. The CCCR has developed an Earth system model, IITM-ESMv2, which is contributing to the IPCC's Sixth Assessment Report (AR6) simulations. The IITM-ESMv2 is one of the participating GCMs in the COALESCE project, while the CCCR has additionally undertaken to provide training to COALESCE modeling groups in adopting data formats evolved in the CMIP6, to enable compatibility with international data formats.

Joint wintertime air pollution campaign over Delhi. A joint, multi-institutional, collaborative field campaign is underway during 2019–21 to characterize the wintertime air pollution over Delhi through the support of the Central Pollution Control Board (CPCB, India). Participating institutes include the Indian Institutes of Technology Kanpur and Delhi; the Paul Scherrer Institute, Switzerland; Physical Research Laboratory, Ahmedabad; Manav Rachna University Faridabad, and the Indian Institute of Tropical Meteorology (Delhi branch).

Aerosol hygroscopicity study in Delhi. A collaborative study campaign by IIT Delhi, Leibniz Institute for Tropospheric Research (TROPOS), and The University of Texas at Austin has been designed to investigate the link between water uptake ability of aerosol and its chemical and microphysical properties over Delhi.

NASA MAIA. NASA's upcoming mission MAIA (Multi-Angle Imager for Aerosols) aims at retrieving speciated $PM_{2.5}$ across the globe on a 1-km grid. One of the key mission objectives is to initiate air pollution epidemiological studies in primary target areas (PTAs), which are major population centers (Diner et al. 2018). The Delhi national capital region is one candidate PTA, considered one of the most polluted regions in the world.

Regional flagship study on Ambient Air Pollution and Public Health (World Bank). The World Bank recently launched a regional flagship study on "Ambient Air Pollution and Public Health." The purpose of this regional flagship study is to fill key knowledge gaps to help South Asian governments design and implement effective policies to reduce the public health threats of ambient air pollution.

NERC–MoES Atmospheric Pollution and Human Health (APHH) program. This program has a stream of activity looking at urban air pollution and its impact on health in Indian megacities, and is a collaboration between NERC, the Medical Research Council (MRC) in the United Kingdom, and the Ministry of Earth Sciences (MoES) and Department of Biotechnology (DBT) in India. The program has a focus on the Indian megacity Delhi to understand the impacts of outdoor urban atmospheric pollution on health.

Time schedule and outlook

The COALESCE project is planned as a 5-yr multi-institutional project (Fig. 6) organized around a three-tier structure involving 22 institutions (Fig. ES1), including a lead institution (Indian Institute of Technology Bombay), 10 associate institutions, and 11 field institutions, working in coordination with the Indian Ministry for Environment, Forests and Climate Change.

It involves participation of over 40 investigators (Table ES1) and, most importantly, over 70 research students and staff. The COALESCE observation network will attempt to fill current gaps in regionally representative observation stations, especially in regard to aerosol chemistry, physics, and optics, in the pan-Indian region. The project would generate important observational data and extensive model results utilizing the full potential of a hierarchy of models: technology-linked energy-emissions modeling, scenario analysis, multivariate receptor models, extended receptor models, regional chemical transport and climate models, and global general circulation models. Design and planning for comprehensive research infrastructure and research methods began in mid-2017. The first 18 months of the project has seen a launch of field campaigns for estimation of human activity influencing key carbonaceous aerosol emission sources and for measurement of field emissions; setup of a regional observation network; and identification, evaluation, and deployment of a suite of climate models on regional and global scales for simulation studies.

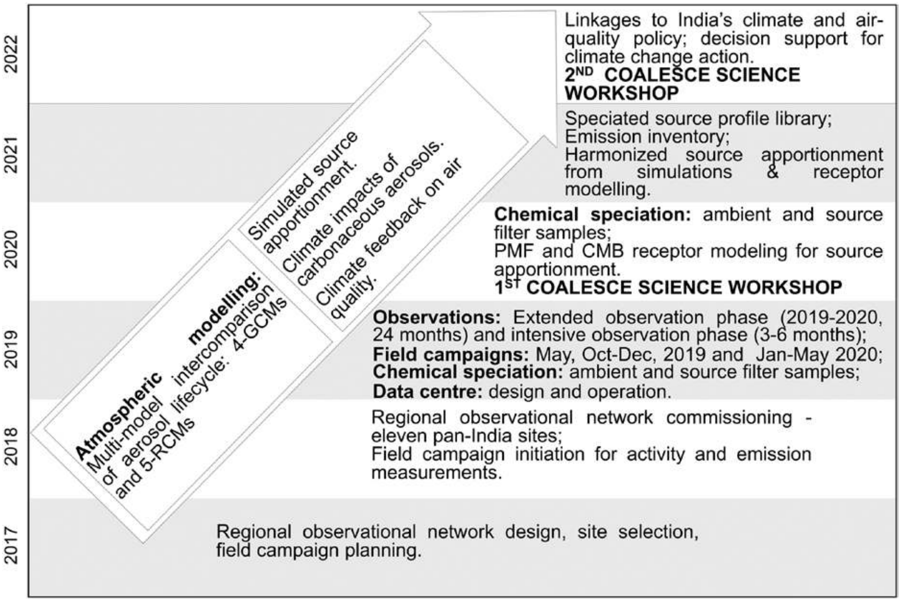

Fig. 6. Tentative timeline for the COALESCE project.

The COALESCE project is envisaged to be a major effort contributing toward building an integrated aerosol, air pollution, and climate research community in the South Asian geographical domain, with key links to international scientists. There are important links to India's national action plans related to air quality and international commitments to climate change. The COALESCE project would attempt to assist in the reporting role of the Indian MoEFCC to UNFCCC, in terms of greater detail in estimated sectoral and total emissions of key SLCPs. We would endeavor to enable India's engagement with international conventions like the Climate and Clean Air Coalition and the Arctic Council (2017). The project is a key step to building a strong knowledge base related to short-lived climate pollutants in India to underpin decision-making on regional climate change. The observational network of regional $PM_{2.5}$ monitoring stations and capacity building in quantitative source apportionment would feed into national $PM_{2.5}$ control strategies and to assessments of health impacts of regional air pollution. Our multidisciplinary approach, using both measurements and modeling, will be further developed during the next years in our effort to meet COALESCE objectives and make a relevant contribution to climate and clean-air action in the Indian region.

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