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Air pollution health research priorities for India: Perspectives of the Indo-U.S. Communities of Researchers

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1. Basis for document on air pollution research gaps in India

This white paper represents the culmination of over 2 years of efforts and bilateral dialog between scientists at Indian governmental agencies, U.S. federal agencies, and academic institutions in India and the U.S. to develop strategies to mitigate air pollution-related health effects and to promote collaborative research initiatives to accelerate a scientific knowledge base that may help accomplish this goal. A series of virtual meetings initiated by the National Institute of Environmental Health Sciences (NIEHS) led to the formation of a

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Communities of Researchers (CoRs) organized around three themes of health research, exposure assessment, and training. Virtual meetings and visits of U.S. scientists at laboratories in India were held over 18 months. The CoRs were successful in identifying gaps in research in the three theme areas and providing research recommendations that were discussed at length at a joint Indo-US Workshop to "Explore Bilateral Research Opportunities to Address Air Quality and Health Issues" in New Delhi, India on November 8–10, 2016. This workshop was jointly sponsored by NIEHS and the Indo-US Science and Technology Forum (IUSSTF) with additional support provided by the Centers for Disease Control (CDC) and the Research Triangle Institute (RTI) and US Embassy, New Delhi, India. The information gathered through all these efforts, including the bilateral workshop, provided the direct basis of this document. The workshop participants also thoroughly reviewed the recent Indian Ministry of Health and Family Welfare report (MHFW (Ministry of Health and Family Welfare), 2015), that provided a comprehensive account on the status of air quality-related health issues in India, and targeted actions aimed at providing the largest exposure reductions (instead of traditional approaches to air quality management) to address the substantial national health burden that can be attributed to both ambient and household air pollution in India (Sagar et al., 2016).

A core group of eight scientists representing each CoRs, through multiple conference calls and exchange of information, developed a set of charge questions for broader discussion at the workshop in New Delhi with the participation of about 100 scientists in the areas of health, exposure and education. The questions were based on the previously identified gaps in knowledge to facilitate a focused discussion around the defined themes of exposure assessment and air pollution health research. Each breakout group consisted of approximately 40 scientists that separately and together deliberated on the major questions. An additional goal was to identify potential opportunities for collaboration and exchange of expertise between the U.S. and India. These collaborations would integrate exposure and health outcomes analyses to demonstrate the health burden due to high levels of air pollution in the Indian population at large. Discussions were also aimed at developing a focused set of research priorities with shared expertise that may be jointly supported by the U.S. and India and identifying critical needs in training and capacity building with advanced technical expertise in air pollution exposure assessment, modeling, and population health research.

2. Background

According to the global air pollution observatory maintained by World Health Organization (http://www.who.int/gho/phe/outdoor_air_pollution/en/), 13 of the world's 20 cities with the highest annual levels of particulate matter < 2.5 μm in diameter ($PM_{2.5}$) are in India, with its capital city New Delhi leading cities within India. Given the challenges in regulation, increasing economic activity, and industrialization across the country, a progressive worsening of ambient air pollution (AAP) in these Indian cities is nearly certain. To add to this burden of AAP, nearly 76% of rural households are dependent on solid biomass as cooking fuels and thus experience household air pollution (HOAP) exposures that greatly exceed World Health Organization (WHO) Air Quality Guideline (AQG) levels (Balakrishnan et al., 2013).

The report on Global Burden of Disease (GBD) estimates 2 million premature deaths annually in India due to AAP and HOAP exposure (GBD (Global Burden of Disease), 2016). This places air pollution near or at the top of the list of all known risk factors for ill health in the country, above high blood pressure, smoking, child and maternal malnutrition, and risk factors for diabetes. However, given the current demographics in India skew towards a more youthful population, there may be a masking of the cumulative cardio-pulmonary effects of air pollution exposures, that will only be observable as latent effect decades later. If $PM_{2.5}$ levels were to remain constant at current levels, it would suggest that the per-capita mortality attributable to $PM_{2.5}$ in India would increase by 21% in the year 2030, aided and abetted by a dramatic increase in the age > 50 population. To even keep $PM_{2.5}$-attributable mortality rates (deaths per 100,000 people per year) constant, the average $PM_{2.5}$ levels would need to be reduced by 20–30% over the next 15 years, particularly to reduce the increases in $PM_{2.5}$-attributable mortality in the elderly. Thus, significant improvements in indoor and outdoor air quality are required to produce a significant reduction in $PM_{2.5}$-attributable mortality in India (Apte et al., 2015).

The strategic direction for air quality improvement in India is hampered by the lack of adequate inventories on emissions and uncertainty in the pollution mixture in ambient air (Garaga et al., 2018). It is likely that both factors differ from what is observed in developed economies of the West. Source emissions can differ significantly in composition, but only limited research in India has addressed the role of $PM_{2.5}$ source and composition on adverse health effects. Initial results suggest that emissions from fossil fuel combustion are of greater health consequence, per μg/m^3 of $PM_{2.5}$, than from biomass or windblown sources (Thurston and Balmes, 2017). However, emissions from indoor cooking using biomass contribute to approximately one-quarter of the mass of ambient $PM_{2.5}$ pollution in the country, suggesting India-specific solutions are needed to additionally address these sources (Chafe et al., 2014). In India, exposure to ambient and household air pollution forms a continuum, owing to the significant penetration of AAP indoors and the substantial contribution of HOAP to outdoor levels. Thus, indoor and outdoor sources cannot be considered in isolation or examined in a compartmentalized manner, but rather as a continuum (Balakrishnan et al., 2014) with a common impact on health outcomes and common approaches to measure, quantify, and control diverse sources that contribute to this problem.

The risk of exposure to air pollution occurs in both rural and urban populations, however, the routine monitoring of air quality, in India and many countries across the globe, is nearly exclusively confined to urban centers (Garaga et al., 2018). This makes the task of understanding the nature and distribution of nationwide population exposures much more difficult. Another important aspect relates to the spectrum of exposures. In India, exposure to locally strong sources such as biomass cooking, trash burning, street food carts, and small industries contribute to large spatial gradients in exposures that are poorly captured by outdoor ambient levels measured at central sites (Pant et al., 2016). Given the high levels of ambient $PM_{2.5}$ in metropolitan areas, where the contributions of HOAP may be dissimilar compared to rural settings, derived exposure-response relationships will be different and need to be addressed adequately in estimating health impacts at the national level (i.e., the $PM_{2.5}$ mixtures are likely to vary significantly between urban and rural populations, and one can also expect the exposure-response relationships to also vary between these two populations). Further considerations in India include additional exposures to air toxics and heavy metals, which are highly prevalent in urban industrial clusters. Several toxic pollutants are co-emitted along with PM and contribute to adverse health risks (Pant et al., 2016; Guo et al., 2017). A comprehensive environmental health assessment should consider factors such as toxicity, emissions volume, potential population exposed, exposure pathways, and health outcomes.

3. Air pollution sources, concentration, and exposure scenarios in India

This section provides a background summary on AAP and HOAP exposures relative to the major sources and emissions in India. Understanding of the unique exposure profiles to air pollution is critical to better understanding of the magnitude of health effects attributable to air pollution and provision of recommendations.

3.1. Ambient air pollution (AAP)

The rapid growth in the industrial, power, and transportation sectors nationally, combined with growth in urbanization, both planned and unplanned, have contributed to the rapid increase in AAP levels in India. Together, the substantial growth in the number of automobiles and coal-based power production are expected to significantly contribute to the worsening of air quality in the next decade in India. For more than half of the cities included in the National Air Quality Monitoring Program (NAMP), two critical measures, $PM_{2.5}$ and PM_{10} (daily and annual levels), routinely exceed Interim Target-1 levels (75 and 150 μg/m^3 for daily and 35 and 70 μg/m^3 annually, respectively), as designated by the WHO.

The assessment of the contribution of emission sources to air pollution is inadequate in India, and limited data are available for sulfur dioxide (SO_2), nitrogen oxides (NOx), and carbon monoxide (CO). Although a decline in the levels of SO_2 has been observed in many cities, these levels are still unhealthy. While the monitoring of ambient air pollution has increased, at least in major cities, there are substantial gaps in monitoring in large parts of the country, especially in rural locations (http://www.cpcb.nic.in/RealTimeAirQualityData.php). Given the critical need to provide a national map of air pollution, remote sensing methodologies are increasingly relied upon and felt to be critical to provide exposure-health effects data and to develop source apportionment information vital to assessment of intervention strategies. Indeed, satellite modeling of aerosol optical depth (AOD) has demonstrated a stark picture of AAP in both urban and rural areas. The Indo-Gangetic Plain registered critical levels of $PM_{2.5}$ (mean annual $PM_{2.5}$ > 50 μg/m^3) attributable to multiple ambient sources, the use of biomass and coal for household cooking and heating needs, and the burning of agricultural residue (Dey et al., 2012).

3.2. Household air pollution (HOAP)

Solid cook fuel emissions result primarily from incomplete combustion. The traditional stoves are extensively used in rural Indian households and typically operate under inefficient conditions of combustion and emit hundreds of different chemical substances, during the burning of solid fuels. Whereas the national air pollution monitoring program in India provides routine air pollution concentrations for many urban centers, the currently available data on HOAP exposures are largely known from scientific publications from individual research studies. Over 200 studies have characterized HOAP exposures in solid fuel-using households of developing countries and a majority of these studies are primarily based in India. The exposure assessment methodology has included questionnaire-based assessments, actual long-term field-based measurements of HOAP, and personal exposures for women, men, and children. A compilation of the quantitative HOAP results, including those in India, is available in the WHO Global Household Air Pollution Database (Balakrishnan et al., 2014).

HOAP exposures are well known to be heterogeneous in composition and have multiple determinants such as fuel/stove type, kitchen area ventilation, and quantity of fuel, age, gender, and time spent near the cooking area. These factors influence spatial and temporal patterns of exposures between as well as within households. Regardless of the variability in results across studies, however, the data provide evidence of extreme exposures in communities using solid cook-fuel to exceed, by several fold, WHO-AQGs.

More recently, due to lack of direct studies quantifying the potential mortality effects of HOAP, modeling approaches such as Integrated-Exposure-Response Curves (Burnett et al., 2014) were utilized to link population-level estimates of HOAP exposure with health outcomes, analysis. This model still needs verification in real-world HOAP-exposed populations, as the HOAP composition and levels of exposure in developing countries is different from developed world HOAP and AAP. The global exposure estimate for solid fuel users in the 2010 Global Burden of Disease assessment (Lim et al., 2012; Smith et al., 2014) was based upon an India exposure model (Balakrishnan et al., 2013). This model utilized $PM_{2.5}$ measurements obtained in rural households and cooking-related household data available in the National Family Health Survey. These models, developed for solid fuel-using households, determined that $PM_{2.5}$ concentrations were up to 337 μg/m^3 (Balakrishnan et al., 2013), and exceed the current WHO-AQG IT-1 of 35 μg/m^3 (WHO, 2006) and the Indian standard of 40 μg/m^3 (Central Pollution Control Board, 2009).

3.3. Sources of air pollution in India

Air pollution sources in urban and rural environments include stationary, mobile, and region-specific emissions. The most commonly identified region-specific emission sources in India are motor vehicles, manufacturing, electricity generation, construction, road dust, agricultural waste burning, combustion of oil, coal, and biomass in the households, and marine/sea salt. The Indo-Gangetic Plain, for instance, has a large number of brick kilns, and is also home to a large population still using biomass and/or coal for combustion needs. The states in the east of India, such as Bihar, West Bengal, Jharkhand, Orissa, and Chhattisgarh, harbor large coal mines and power plants in conjunction with extensive biomass use, making these areas among the most polluted parts of the country.

Vehicular emissions represent the most rapidly growing source of air pollution in cities and urban neighborhoods. Thirty cities have at least 30% of the households which own a 2 wheel motor vehicle, and 19 major cities have at least 10% households with a 4 wheel car or utility vehicle. The transport sector has seen an exponential increase in highway freight and the use of diesel. Using GIS-based methods, Jerrett and colleagues have determined that nearly 55% of the population (~7.8 million people) in Delhi resides within 500 m of roads, and is, therefore, at increased risk from traffic pollution (Jerrett et al., 2010). Exposure assessment of commuter exposures in Delhi (Apte et al., 2011) has demonstrated that the in-vehicle $PM_{2.5}$ concentrations are at least 1.5 times higher than corresponding ambient $PM_{2.5}$ concentrations.

In addition to vehicular sources in India, there are several other unique sources that contribute to a substantial proportion of AAP. These include trash burning, unregulated use of personal diesel generator sets, brick kilns and local industries, and power plants. Local dust sources such as areas with little green cover, construction sites, and resuspension of road dust, are major contributors to PM levels. The air quality in cities is often heightened by meteorology with substantial variations in temperature, humidity, and rainfall between winter and summer. The use of biomass, primarily for heating, is thought to be responsible for as much as 30% of PM pollution in winter and, together with weather factors such as "inversions" and the burning of agricultural waste, may significantly elevate winter levels, particularly in large cities such as Delhi. In 2010, the portion of outdoor combustion-derived $PM_{2.5}$ pollution attributable to indoor solid fuel-cooking was estimated to be around 26% in India (Chafe et al., 2014). These indoor sources are a substantial contribution to outdoor air pollution and, thus, are particularly important from a health perspective as the indoor-generated air pollutants can silently and disproportionately contribute to ambient air pollution in rural/semi-urban areas.

4. Air-quality monitoring in India

The air monitoring network in India is rapidly expanding. AAP information is collected primarily by the Government of India's National Air Quality Monitoring Program (NAMP), administered by the Central Pollution Control Board (CPCB), which is part of the Ministry of Environment, Forests and Climate Change, Government of India. The primary responsibility for conducting air quality monitoring is shared by the CPCB (national level) and the State Pollution Control Boards (state level), as well as the Pollution Control Committees in Union territories. The National Environmental Engineering Research Institute (NEERI) and a few academic research institutes also carry out pollution monitoring but on a limited scale. Delhi and Pune have citywide monitoring networks, administered by the Ministry of Earth Sciences, which are outside the NAMP monitoring network (Beig et al., 2013). Measurements of criteria air pollutants have also been reported in many individual studies. The CPCB revised National Ambient Air Quality Standards in 2009 to include 12 pollutants (SO_2, NO_2, PM_{10}, $PM_{2.5}$, ozone, lead, arsenic, nickel, CO, NH_3, benzene, and benzo-a-pyrene (BaP)) with regular monitoring of SO_2, NO_2, and PM_{10} by the NAMP, while ozone is monitored in a few mega cities. Other pollutants, such as air toxics (benzene, toluene, and xylene - BTX), BaP, arsenic, and nickel are being monitored on a more limited scale but the capacities are being expanded. Although ozone is listed as a regulated pollutant, its monitoring is extremely limited in a few cities and is currently not reported under NAMP.

Although there is a wish to have a more concerted effort to monitor air pollutants across India (about 248 cities in India as of May 2015), there is a time lag in data reporting and the specific monitoring capacity for $PM_{2.5}$ is very limited. The MOEF/CPCB have recently developed an 11 city network which provides air quality index (AQI) and Bulletins, based upon ozone, $PM_{2.5}$, PM_{10}, NO_2, among others, in near real-time. To address the paucity of ambient air quality data in rural areas, hybrid models that utilize satellite data in conjunction with emissions inventories have been used to derive estimates of global ground-level $PM_{2.5}$ concentrations (van Donkelaar et al., 2010; Brauer et al., 2012). These first-level estimates constitute the primary exposure metrics for the GBD assessment for AAP. These studies have led to further understanding of the regional distribution of air pollution in India and the finding that $PM_{2.5}$ concentrations in the populated rural areas of the Indo Gangetic Basin (IGB) are higher than the $PM_{2.5}$ concentrations in many urban centers located within the Indian peninsula. The satellite extraction data are available at only 0.1° resolution (~10 km), so there is uncertainty associated with these derivative measurements. Inclusion of in-situ measurements and an analysis of spatio-temporal variability in relation to WHO-AQG levels have been evaluated as refinements to this method (Dey et al., 2012).

4.1. Personal monitoring

Air pollution concentrations measured at fixed locations can differ substantially from those derived from personal exposure assessments made in the same microenvironments (Breslin et al., 1967; Rodes et al., 1991; Pant et al., 2016). Personal exposures are dependent on many influencing factors, especially the time-weighted proximity to emissions from both distant and localized sources. Fixed-location monitors do not incorporate the element of proximity, nor do they account for time the person is near the source, thereby leading to potential exposure misclassification (Rodes and Thornburg, 2012). Exposure misclassification can bias the relative risk estimates measured in epidemiological studies (Flegal et al., 1986) or the (pre-) clinical associations of physiological changes resulting from air pollution exposure (Brook et al., 2011).

The continued evolution of more powerful and lower cost microelectronics in conjunction with new manufacturing practices such as 3D printing has enabled the development of low-burden, low-cost air pollution sensors. A plethora of new air pollution sensors designed specifically as wearable systems for personal exposure monitoring are now available for use in research and citizen scientist studies. These new systems have a lower participant burden compared to older personal exposure systems (Williams et al., 2009), and the weight and noise reductions translate to higher study protocol compliance among participants thereby increasing the quality of the exposure data (Lawless et al., 2012). Low burden personal exposure monitors also enable exposure monitoring of children as young as 3 years old that have greater susceptibility to the health impacts of air pollution (Chartier, 2016). Commercially available sensors from North American, European, and Chinese manufacturers are available in India. The reliability and data quality varies greatly between individual sensors so a user must carefully review independently generated performance data or collect their own data (Williams et al., 2014a; Williams et al., 2014b; http://www.aqmd.gov/aq-spec). Also, in many cases, the low cost sensors have a limited range of linear response and therefore calibration may be necessary. Since 2016, > 20 India-based companies have started producing low-cost air quality sensors; however, the wide-scale availability and quality of these sensors are unknown.

Personal exposure monitoring has an important role in future Indian air pollution health research because exposure misclassification can be minimized. Exposure characterization studies using wearable sensors can identify the sources of AAP or HOAP that comprise a population's exposure to PM, NO_2, O_3, and other gases (RTI International, 2013). Given the high AAP and HOAP concentrations in areas like the Indo-Gangetic Plain, exposure characterization studies will provide preliminary data to guide policy interventions to reduce AAP or HOAP. Exposure characterization data will also inform the design of studies to link air pollutants to specific acute and chronic disease exacerbations (Dutmer et al., 2015). Eventually, large scale epidemiological health affects studies that use a combination of personal exposure monitoring, satellite measurements, and traditional ambient air quality measurement networks will provide quantitative data for assessing the health impacts of air pollution in India where the dynamic economic, cultural, and climatological conditions may hinder traditional approaches.

4.2. Air quality standards in India

The Indian Central Pollution Control Board (2009) revised the annual average PM_{10} to 60 μg/m^3 which is lower than the Interim Target 1 (IT-1) guideline value of 70 μg/m^3 recommended by the WHO (2006). The annual average PM_{10} levels reported by CPCB (> 90 μg/m^3) is routinely higher than the recommended guideline values across most locations in India. The CPCB recommended annual average value for $PM_{2.5}$ (40 μg/m^3) is higher than WHO recommended value (35 μg/m^3) and similar to PM_{10}, the annual average $PM_{2.5}$ levels are higher than the guideline values in most locations throughout India. The situation is similar for NO_2 and SO_2, with the annual levels for these pollutants exceeding, by a substantial margin, the 24-h WHO-AQG levels.

It is of critical importance to realize, however, that the above standards are based on the study of air pollution mixtures from countries in Europe and North America, which, especially in the case of PM attributable to AAP and household sources, may not be directly transferrable to locations in much of India. It will be necessary, therefore, to evaluate the source-specific components of PM air pollution in India, for comparison with that in other parts of the world, as well as to the conduct of local studies of the health-air pollution relationship in India. Especially important will be the collection and analysis of $PM_{2.5}$ samples at a variety of locations across the country, and statistical analyses of the health effects relationships in urban centers and rural areas, as a function of composition and source. This will be an ideal opportunity for initiating a collaborative study by the US and Indian scientists

5. Air pollution and epidemiology in India

The vast majority of epidemiological studies reporting health effects associations with AAP in India use data from urban centers, and mostly report on prevalence of respiratory morbidity. A systematic review of the literature on the health effects of ambient air pollution in Asia published by the HEI (Health Effects Institute) (2011) identified 43 studies carried out between 1980 and 2008, that reported adverse health effects of air pollution in India. These studies, largely concentrated in the cities of Delhi and Mumbai, reported that the prevalence of diminished lung function, acute and chronic respiratory symptoms such as cough and wheeze, and asthma in children and adults was increased in areas with elevated levels of air pollution.

There are limited time-series analyses that have reported increases in acute respiratory illness (Bladen, 1983), all-cause mortality (Cropper et al., 1997), and emergency visit for cardio-respiratory conditions (Pande et al., 2002). More recent time-series studies report increased rates of natural all-cause mortality with short-term (daily) exposure to PM_{10} in Chennai, Ludhiana, and Delhi (Balakrishnan et al., 2011; Kumar et al., 2010; Rajarathnam et al., 2011). Studies using similar methods have also been reported for other cities and time periods (Dholakia et al., 2014; Maji et al., 2017). The estimates of changes in daily rates of mortality associated with short-term PM exposure observed in these studies are similar to those reported in multi-city studies conducted in China, South Korea, Japan, Europe, and North America (Wong et al., 2008). In addition, a growing body of literature reports that acute health effects are associated with episodic extreme air pollution events such as crop burning (Awasthi et al., 2010; Pande et al., 2002), use of fireworks during Diwali (Parkhi et al., 2016), and in critically polluted areas within large cities (Kumar et al., 2007; Siddique et al., 2011).

Using the 2015 Global Burden of Disease (GBD) assessment, approximately 1.09 million premature deaths and 29.6 million disability-adjusted life-years (DALYs) were attributable to HOAP resulting from solid cooking fuels in India, whereas 977,000 premature deaths and 27.3 million DALYs were attributable to AAP in India from $PM_{2.5}$ exposures. Among the 60+ risk factors examined in the 2015 GBD assessment, the combined burden from AAP and HOAP exceeded the burden from any other risk factor in the list, including individual risks from smoking, diet, or high blood pressure.

Due to the unavailability of India-specific data from epidemiologic studies (multi-city time series or long term cohort studies) that can provide estimates for the effect of long-term exposure on cardiovascular mortality and morbidity and impact on life expectancy, the results of studies conducted in North America and Western Europe have been used to estimate disease burden in India (Burnett et al., 2014; MHFW (Ministry of Health and Family Welfare), 2015). The similarity between risk estimates for effects of short-term exposure on daily mortality for India and global estimates is however noteworthy, especially given the differences in concentration ranges, source mixtures, demographics, and underlying disease rates, and supports the idea that the temporary use of international studies to estimate Indian disease burden is a good first order approximation. In addition, a limited number of population studies carried out in India corroborate the broader global evidence for the higher incidence of chronic non-communicable respiratory and cardiovascular diseases in India (Basu et al., 2001; Dutta et al., 2012; Lahiri et al., 2000; Ray et al., 2006; Roy et al., 2001; Roychoudhury et al., 2012).

Unlike studies of AAP that have characterized exposure to air pollution in terms of estimated levels of PM and other pollutants, most epidemiologic studies of HOAPs have used qualitative indicators to characterize exposure, such as the use of solid vs. clean cook-fuels, involvement in cooking, or proximity to stove. As reviewed by Smith et al. (2014), several Indian studies are currently included in systematic reviews/meta-analyses used by the GBD efforts to estimate HOAP-related risks for COPD.

As discussed above, the use of Integrated Exposure-Response functions (IERs) with AAP, second hand smoking, and active smoking have allowed the development of HOAP risk estimates for ischemic heart disease and other respiratory diseases reported in the GDB assessment. The HOAP exposure model used in the GBD assessments is based upon measurements and modeling results from India, with estimated daily average $PM_{2.5}$ exposures of 285, 337, and 204 μg/m^3 for children, women, and men, respectively (Balakrishnan et al., 2013; Smith et al., 2014). The current IERs, however, need to be improved by the development of data on the potential for acute and chronic health effects at high levels of air pollution commonly encountered in India. For example, a recent analysis of $PM_{2.5}$ and mortality in China found that, in less urban parts of the nation (where biomass is a major source), there was a leveling of health effects with increases in $PM_{2.5}$ (Chen et al., 2017). However, this “leveling off” of AAP-associated health impacts was not seen in the more urbanized Eastern part of the nation, where fossil fuel emissions are more dominant, perhaps suggesting that high levels of $PM_{2.5}$ from biomass burning are of lesser human health impact per μg/m^3 than elevations in fossil fuel combustion-derived air pollution (Thurston and Balmes, 2017).

Recently launched epidemiologic cohort studies are making efforts to estimate the effects of long-term exposure to ambient and household air pollution on a range of maternal (birth weight), child (acute respiratory infections), and adult (chronic respiratory symptoms and lung function) health outcomes in populations residing in both urban and rural locations (Balakrishnan et al., 2015). The exposure estimates from these studies are being applied in other long-term cohort studies examining cardiovascular risk factors such as high blood pressure, brachial artery hyper-reactivity, and carotid intima-media thickness (Thanikachalam et al., 2015). Recent developing-world cohort studies of the mortality impacts of biomass burning exposure, while limited, suggest that mortality effects from HOAP are, unlike AAP, primarily due to respiratory effects and not cardiovascular (Alam et al., 2012; Mitter et al., 2016), but more direct assessments are needed in India to assess their applicability.

Major gaps remain in our understanding as to the relationship between air pollution exposures and health in India, including: 1) the relationship between $PM_{2.5}$ mass concentrations and both morbidity and mortality (as opposed to PM_{10}, which includes coarse particles); 2) the extent to which these $PM_{2.5}$-health relationships vary across the nation; and 3) how variations in the source and composition of PM impact the toxicity of the PM over space and time. By evaluating these aspects of the $PM_{2.5}$-health relationship, control measures can be devised that better optimize the public health benefits of future air pollution mitigation measures. This information will also be potentially useful in making public health-based decisions regarding control strategies for climate mitigation measures, allowing and optimization of the clean air health co-benefits of CO_2 reduction plans.

6. Recommendations

The breakout group discussion on the charge questions (Tables 1 and 2) and a more expanded discussion around identification of gaps in knowledge, resources, expertise, and technology, as well as how these gaps can be filled with a collaborative research effort among U.S. and Indian scientists, led to a set of Health Effects and Exposure Assessment research priorities. The research and policy priorities identified in these deliberations were grouped into short-, medium-, and long-term goals aimed at providing scientific bases for developing prevention and intervention strategies that may aid in reducing the air pollution health burden in India. The overarching goal of the conference was for scientists from India and the U.S. to jointly identify and prioritize bilateral research collaborations to study the health consequences of India's air pollution and its future reductions. In general, the short-term priorities were based upon research designs that encompassed readily available data sets or that were needed to answer urgent public health concerns. A group of training recommendations was also developed to address long-term capacity building.

A. Health effects assessment recommendations

There was widespread agreement of the critical need for India-specific data on air pollution health effects and dissemination of these data to the public, medical community, and policy makers.

A1. Short-term research priorities in health

1. Initiate retrospective analyses of available health and exposure data with a focus on developing exposure-response relationships. This could include expanding the limited base of time-series studies (Balakrishnan et al., 2011; Kumar et al., 2010; Rajarathnam et al., 2011) to multiple cities or an extended time-series study in a single city based on data availability/quality. Multiple existing cohort studies were enumerated by the group, thus opening up the possibility of adding retrospective exposure data to on-going cohorts.

2. Initiate retrospective analyses of available health and exposure data during recent smog episodes in National Capital area (2015, 2016) such as hospital/clinic visits, hospital admission, prescription of drugs for asthma, pulmonary infection.

3. There was an overwhelming recognition for the need to focus on high profile “charismatic” health outcomes that would have a strong impact on public perceptions and policy makers, potentially including studies involving children (e.g., asthma), birth outcome studies (e.g., birth weight), cardiovascular events (e.g., acute coronary syndrome and heart failure), and cognitive outcomes (e.g., IQ). These studies can be carried out on select major cities and national and state capitals.

A2. Medium/long-term research priorities in health effects

1. There are opportunities to utilize a number of intervention studies that could be initiated based on the proposed policy/regulatory decisions on either a medium- or long-term basis.

2. Several natural experiments could serve as “low hanging fruits”that could readily provide such an opportunity. Examples include the:

   Upcoming fuel conversions (e.g., to natural gas: see Yinon and Thurston (2017)).

   Upcoming auto diesel engine Euro VI/reduced sulfur diesel fuel.

   Moveable/mobile studies.

   Examination of the effect of odd/even car data or similar such policy changes across India.

3. Remediation experiments can also incorporate panel studies that would be useful as intervention studies such as:

   Cost effectiveness of different room filtration systems. Efficacy of different particle masks and indoor filtration systems or combination of these approaches to reduce personal exposure and health effects.

4. Development of a data infrastructure to aggregate health effects data would help further air pollution health research. The electronic consolidation of emergency department (ED) visits and hospitalization records can provide a wealth of information in documenting and tracking the potential health effects from air pollution. In the U.S., syndromic surveillance databases, primarily designed for identifying and tracking disease out-breaks, have been used to document a wide range of public health concerns including the potential cardiovascular effects of acute exposure to air pollution.

B. Exposure monitoring and estimation recommendations

B1. Short term research priorities in exposure

1. There is an urgent need to build a comprehensive nationwide air pollution monitoring network that provides reliable and real time air pollution information on criteria pollutants, including composition of fine particulate matter mass. This should focus on integrating current networks and expand access to rural areas given the significant differences in composition and exposure between urban and rural populations.

2. There is a need to develop effective communication strategies to inform the public about air pollution data (e.g., from real-time monitors) via an index such as the air quality index (AQI). These may include posting AQI via mobile applications, as well as at bus/train stations and airports, accompanied by relevant health warnings and appropriate response measures for different sectors of the society (e.g., school kids, industries, old people, etc.).

3. Meteorological data from the Indian Meteorological Department should be made available online and preferably with air pollution data to enhance impact and understanding among public. Adding temperature (which acts as a stressor) data along with the AQI would draw the attention of the public and make them aware of the AQI metric.

4. Small-scale industries are numerous and can represent major local sources of air pollution (e.g., brick kilns, diesel generator sets, etc.). Therefore, it is recommended that emissions from these sources are measured and/or estimated periodically and tracked either through periodic fence-line monitoring or through ambient monitors in industrial zones that are representative of these source emissions impacts.

5. There is a need for a common data portal to archive and share all the ambient and emissions monitoring data from government, academic/research laboratories, and other sources. This data portal may include:

   a. Metadata and data quality metrics (uncertainty, minimum detection limits, flow rates, instrument maintenance, etc.).

   b. Retrospective monitoring data for $PM_{2.5}$ and PM_{10} measurements are available back to 2010 and 2002, respectively.

   c. Satellite data for PM and gas concentrations have been collected since 2000.

   d. Exposure modeling efforts to predict historic exposure concentrations for urban centers and rural areas across India.

6. Initiate efforts to support QA/QC (Quality Assurance/Quality Control) work on CPCB monitoring data with additional resources or partnership with other government labs/agencies.

   a. Autonomous body to develop and implement standardized protocols for monitoring periodic calibration and verification of instruments across government agencies, national laboratories and academic institutions including developing consistent procedures for onsite calibrations.

B2. Medium/long term research priorities in exposure

1. Significant capacity building is needed for:

   a. State-of-the-art estimation and modeling methodologies should be developed. Also, published modeling studies have focused on urban megacenters in Northern India and more regional and localized modeling studies are necessary to sufficiently evaluate smaller cities and rural areas (e.g., Garaga et al., 2018).

   b. Region or locality-specific indigenous emission factors are required to be developed and utilized for all source categories to ensure representative emission estimates. (e.g., monitoring emissions from major local sources such as biomass burning and diesel generator sets).

   c. All emission profiles should be made available through an open data platform.

2. Access to technologies for chemical speciation data on emissions to identify emission signatures in more extended urban areas as well as rural areas. These

efforts should integrate satellite data and low-cost sensors for unmonitored areas, in order to guide the siting of additional air quality monitors in rural and urban areas.

3. Additional infrastructure needs:

Comprehensive monitoring “Supersites”, including chemical speciation (e.g., Solomon et al., 2008).

Calibration of air monitors to maximize data quality.

Testing and validation of low-cost sensors being developed in India.

4. Promote citizen science efforts with access to a common portal to share personal monitoring data from diverse low-cost sensors.

   a. Guidance for calibration, data QA/QC.

C. Communication and policy recommendations

1. There is a need to develop effective communication strategies to inform the public about air pollution data (e.g., from real-time monitors) via an index such as the air quality index (AQI). These may include posting AQI via mobile applications, as well as at bus/train stations and airports, accompanied by relevant health warnings and appropriate response measures for different sectors of the society (e.g., school children, industries, old people, etc.).

2. Establish collaborative partnership with media to promote dissemination of reliable, accurate, and balanced news and data are valuable members of this framework to promote widespread public awareness.

3. Integrate citizen science with community health warnings to local areas, especially during high air pollution episodes.

4. The research agencies such as ICMR and CSIR under the Ministry of Health and Family Welfare, and the Prime Minister's Office should promote collaborative research with ongoing air pollution exposure assessment of epidemiological studies funded by National Institute of Health, USA, European Union and NGOs.

D. Training needs recommendations

The breakout group identified a near absence of environmental public health education opportunities in India and how U.S.-India collaborative efforts can aid in addressing this critical need. One of the short term priorities was to develop a mechanism for developing curricula/field training in environmental public health, initially focused on air pollution epidemiology and toxicology. This can be initiated with short-term professional training courses through development of exchange visitors program as well as via visiting faculty from the U.S. offering hands-on courses across geographical regions of India. The groups also identified training needs for young investigators, graduate students, and established faculty refocusing their research in environmental public health, including:

1. Fundamentals of environmental epidemiology and toxicology:

    a. Study design (questionnaire-based surveys, daily catalogs of activities)

    b. Monitoring [collection of environmental and biological samples]

    c. Integration of exposure and health data.

2. Capacity building – personnel and state of the lab Core laboratories with analytical capabilities for environmental and biological samples.

    a. short term priority to identify existing expertise across government agencies, national labs, and universities and provide resources and access to support air pollution health research in areas such as targeted/ untargeted metabolomics, genetic/ epigenetic, clinical diagnostic markers.

    b. analytical capabilities for chemical speciation of environmental samples

3. Creation of national/regional databases and repositories for exposure and biological data. While many studies of exposure have been conducted in India, the data are not always easily accessible for further research or meta-analysis. Training in the availability, transparency, and documentation of the data behind existing research would further research in the area of air pollution and health.

4. Exposure monitoring and modeling. Optimal utilization of existing exposure and health data requires the training of individuals in biostatistics and epidemiology with an emphasis on exposure assessment data modeling.

7. Conclusions

The goals of the two-year bi-lateral dialog between researchers in India and the U.S. provided a fruitful exchange of information and mutual understanding that resulted in taking stock of the state of research of air pollution health research in India. These interactions resulted in identifying the research gaps, needs and potential opportunities for sharing of expertise, technology, and experience from the U.S. Through these interactions over the two years by a small group of scientists, a set of charge questions was developed for a focused discussion by a larger community of scientists that worked in isolation at the two-day workshop held in New Delhi, India. The goals of this workshop were to deliberate on the charge questions and develop consensus on recommendations to promote active collaboration, access to expertise, required training to bring the state-of-the-art environmental health expertise (e.g., environmental epidemiology, exposure assessment, source characterization, and chemical speciation). In addition, opportunities for short-term training by an exchange of visitors across the U.S. and India were recognized. It's our hope that the recommendations developed here will: 1) facilitate joint activities among experts from India and the U.S.; and 2) promote potential opportunities for U.S. and Indian research funding agencies to collaboratively develop research and training programs to address the research needs previously identified (MHFW (Ministry of Health and Family Welfare), 2015).

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Table 1

Charge questions on air pollution health research issues in India.

Number	Charge question
1	Do we have the required health and exposure data to carry out a retrospective analysis to assess air pollution related health effects at city/town/village level?
2	What are the basic research questions that can be jointly addressed with analysis/re-analysis of existing exposure and health data?
3	Given the prevalence of high levels of air pollutants year-long in certain areas of the country and based on our understanding from the air pollution health research literature, can we identify and prioritize assessment of chronic diseases in India influenced by poor air quality?
4	If so, do we have the access to health and exposure data to initiate a Indian multi-city time series study, for example: mortality, hospital admission and emergency room visit or increased prescription of asthma medication?
5	What are the most critical training needs that enable conducting short/long-term health effects studies in the country (e.g., epidemiological study design, field data collection methods, creation of databases that utilize surveillance data, multivariate statistical analyses)?

Table 2

Charge questions on air pollution exposure assessment in India.

Number	Charge question
1	How many stationary monitoring sites collect continuous monitoring data across India, especially in metropolitan and rural areas? Do we have access to these data?
2	What kind of air pollution source apportionment, chemical speciation, and temporal and spatial variation data are available (or can be made available for rapid analysis)?
3	What kind of technological expertise is available (e.g., satellite, personal monitoring) and, if so, what efforts are underway on integration of data across spatio-temporal exposure assessment?
4	What are the critical training needs for exposure assessment (e.g., design and collection of field environmental data, personal monitoring/biomonitoring methods, laboratory analyses, exposure modeling)?