Implications of Implementing Promulgated and Prospective Emission Regulations on Air Quality and Health in India during 2030

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ABSTRACT

To improve ambient air quality, India has laid out strict action plans to reduce the increment in emissions over regional to urban scale by the year 2030. This study evaluates policy-induced improvement in air quality and associated health benefits achievable due to reduction in PM₂.₅ exposure under the adoption of promulgated (S2) and ambitious prospective regulations (S3) with respect to the scenario for Business As Usual (BAU) in 2030. The Weather Research and Forecasting model coupled with online chemistry (WRF-Chem) has been used to simulate ambient PM₂.₅ exposure to the population under BAU, S2 and S3 emission scenarios. Results show 15% (9 μg m⁻³) and 49% (32 μg m⁻³) decreases in all India ambient PM₂.₅ exposure under S2 and S3 scenarios, respectively, with respect to the BAU scenario. Throughout India, under the S2 and S3 scenarios, 38% and 62% of states would meet the annual National Ambient Air Quality Standard (NAAQS) of 40 μg m⁻³, respectively. We projected that the S2 emission regulation scenario would prevent 274,000 (8.3%) premature mortalities and improve mean life expectancy by about 0.6 ± 0.2 years in 2030 relative to the BAU scenario. On the other hand, pursuing an ambitious emission scenario, S3 would prevent 775,000 (~23.6%) premature mortality burden and improve mean life expectancy by about 1.9 ± 0.7 years in 2030. Results indicate that ambitious actions beyond the ambitious prospective regulations are vital to gain significant health benefits.

Keywords: Air quality, Premature mortality, Emission scenarios, Particulate matter, WRF-Chem

1 INTRODUCTION

As part of the initial commitments to the Paris agreement in December 2015, India has committed to the conservation and protection of the environment with sustainable development within the ambit of targeted goals to reduce the increment in emissions with respect to the scenario for Business As Usual (BAU) by the year 2030 (MoEFCC, 2015). Though India’s propositions are observed to be ambitious to meet all the targets in a span of 15 years, the government is committed to enforcing policy-induced measures to cut down emissions. As an emerging economy, India faces enormous challenges due to various issues, including increasing energy demand due to its higher population growth rate. These challenges can be related to ensuring intended economic growth,
overall infrastructure development and an increase in industrial and service sectors’ activities. In the past three decades, the industrial developments in India have escalated to new heights, which consequently have led to multiple urban environmental issues (Hakkim et al., 2019; Ghude et al., 2020a), especially deteriorating air quality and giving rise to health hazards (Ghude et al., 2016; Chatterjee, 2016). Therefore, air pollution has become a matter of serious concern for public health in India. As per United Nations Development Programme, India is the world’s second-largest populated country with the most densely populated Indo-Gangetic Plain region (UNDP, 2017), consuming 6% of the world’s total primary energy resources (IEA, 2015). Purohit et al. (2019) identified that the largest PM$_{2.5}$ concentrations occur in the Indo-Gangetic Plain and a clear north-south gradient exists in the PM$_{2.5}$ concentrations over India. In a recent study by Pandey et al. (2021), the authors showed that the ambient particulate matter exposure was 91.7 µg m$^{-3}$ in India in 2019 with higher exposure to particulate matter concentrations of 123.5–217.6 µg m$^{-3}$ found in the northern states of the Indo-Gangetic Plain region. Several past and recent studies using observational and model simulations (Di Girolamo et al., 2004; Jethva et al., 2005; Nair et al., 2007; Chate et al., 2013; Ghude et al., 2013, 2020b; Lena et al., 2015a, 2021; Kumar et al., 2018; Wu et al., 2019; Kaginalkar et al., 2022; Sengupta et al., 2022) have shown higher levels of air pollutants in densely populated urban areas of India making the population of these urban centres prone to higher health risk due to poor air quality (Chate et al., 2013; Greenstone et al., 2015; Surendran et al., 2015; Ghude et al., 2016; Cohen et al., 2017; Conibear et al., 2018a, 2018b; Guo et al., 2018; Chowdhury et al., 2019; David et al., 2019). Lelieveld (2017) examined that the steepest increase in mortality attributable to air pollution occurs in South Asia, especially in India. Using the regional Community Multi-scale Air Quality (CMAQ) model over northern India, Karambelas et al. (2018) estimated 463200 premature adult deaths from PM$_{2.5}$ exposure using emission estimate for the year 2010. A recent study by Balakrishnan et al. (2019) revealed that India has a disproportionately high mortality and disease burden due to ambient air pollution, where the burden is highest in the states of north India with low Socio-demographic Index (SDI). According to World Health Organization (WHO) statistics, about 1 million non-accidental deaths/premature mortality estimated in 2017 were due to population exposure to high levels of air pollution in India (IHME, 2018). The Global Burden of Disease Studies (Murray et al., 2020) reported that exposures to ambient and household particulate matter pollution are among the major causes of premature mortality in India.

Given the high pollution level and associated health impacts, targets and actions for reducing emissions are integral components of the sustainable growth agenda of the Indian government. Therefore, in an affirmative and ambitious approach, the Indian government has laid out several mission modes, and strict action plans to reduce the regional to urban scale emissions. In principle, these action plans limit the emissions by 2030 and 2050 to the extent that would achieve the intended economic growth. In April 2015, the Ministry of Environment and Forest and Climate Change (MoEF & CC, Govt. of India) launched a National Clean Air Program (NCAP) as a major assertive program to improve urban air quality in urban regions mitigating public health risk. In this context, the Indian government has taken many strategic plans under the sustainable development goals (SDGs) with relevant administrative and regulatory measures considering the advancement in technology, infrastructure availability, development of path transformation, and enhanced public awareness. The Government of India launched Deen Dayal Upadhyay Grameen Jyoti Yojana in 2014 (https://www.india.gov.in/spotlight/deen-dayal-upadhyaya-gram-jyoti-yojana), and Pradhan Mantri Ujjwala Yojana 2016 (https://www.pmujjwalayojana.com/about.html) which was intended to replace kerosene and solid-fuel with cleaner fuel for household lighting and cooking. The recent introduction of urban development plans such as the Atal Mission for Rejuvenation and Urban Transformation (AMRUT), Smart Cities Mission, and Housing for All (Urban) by the government of India are modes to increase the opportunities for megacities which are considered as “growth engines”. India is poised to have 100 smart cities and 20 million houses to be constructed in the next few years. Major policy decisions that the government has undertaken within the ambit of targeted SDGs to augment abatement of air pollution are: (1) promulgated nationally determined contribution of 40% to renewable energy in 2030, (2) share of growth in public vehicles (25–30%), (3) leapfrogging from BS-IV standard to BS-VI standard and awareness about large scale usage of electric vehicles, (4) shift to energy-efficient technologies and fuels (55% in 2030), (5) 35% phase-out in agricultural residue burning by 2030, and (6) expansion of cleaner fuels...
like CNG, LPG, natural gas and ethanol blending. With these recent policy interventions, emissions are projected to reduce in 2030 and 2050, particularly with respect to fine particulate matter (PM$_{2.5}$) levels as compared to no policy-induced baseline interventions for Business As Usual (BAU) emission scenarios (Venkataraman et al., 2018).

It is, therefore, important to address the broader question of whether current policies are already putting India on a path of mitigating public health risks. This work aims to look into the policy projections of emission reduction by 2030 to improve air quality. In this perspective, we assess the implications of ongoing assertively implemented policies aimed at reducing emissions and thus improving public health by reducing population exposure to PM$_{2.5}$ ambient levels by 2030. Apte et al. (2015) re-iterated that major improvement in air quality is a crucial requirement to significantly reduce mortality from PM$_{2.5}$ in the polluted regions of India. Their findings showed that in order to keep PM$_{2.5}$ attributable mortality rates (deaths per 100000 people per year as per 2010 estimate) constant, the average PM$_{2.5}$ levels would need to decline by ~20–30% by 2025 to balance the increase in PM$_{2.5}$ attributable mortality from ageing populations. Using the WRF-Chem model, Conibear et al. (2018b) estimated the impacts of three different air pollution control pathways viz. (i) New Policy Scenario (NPS), (ii) Clean Air Scenario (CAS), both developed by the International Energy Agency (IEA), and (iii) Emission source-based scenarios (such as residential, energy, industry, and transport), on the ambient PM$_{2.5}$ concentrations and human health in India in 2050. The NPS includes all existing and planned policies (as of 2016) that contribute to the reduction in air pollution and the CAS represents a set of aggressive policy actions aimed to achieving significant additional reductions in pollutant emissions, and customized to national circumstances (IEA, 2016). The authors found that the NPS and CAS could reduce population-weighted ambient PM$_{2.5}$ concentrations below 2015 levels by 9% and 68%, respectively. Purohit et al. (2019) have explored the effectiveness of policy interventions on PM$_{2.5}$ exposure and health impacts using a multi-disciplinary scientific framework consisting of the Global Change Assessment Model (GCAM) model and the Greenhouse gas - Air pollution INteractions and Synergies (GAINS) model. Their analysis highlighted that in many Indian States, the emission sources outside the immediate state jurisdictions make the dominating contributions to the ambient particulate pollution levels. Therefore, reduction in emissions in the surrounding regions and regionally coordinated cost-effective strategies are necessary to mitigate the exposure to ambient particulate pollution in a region. Considering four different emission scenarios, they have also found that advanced technical emission control measures, combined with national sustainable development strategies, could provide NAAQS-compliant air quality for majority of the Indian population by 2030.

It is imperative to have a proper understanding of pollutant emissions from different emission sectors, considering both the present-day conditions and future time-elapsed evolution under various socioeconomic pathways of development along with shifts in science and technology to undertake strategies to mitigate air pollution. In this work, considering the projected population of India by 2030, we have considered three emission scenarios developed by Venkataraman et al. (2018) which extend from 2015–2050 as: (1) reference scenario Business As Usual (BAU), (2) aspirational scenario (S2) and (3) ambitious scenario (S3). These scenarios capture varying levels of emission control, with BAU representing no change in current (2015) regulations corresponding to slow implementations of new technologies, S2 representing adoption of promulgated regulations corresponding to the effective achievement of targets and S3 representing adoption of ambitious prospective regulations corresponding to those well beyond promulgated regulations. In their study, the methodology adopted for the future projection of emissions included growth in sectoral demands, technology mix, energy consumption, and technology-linked emission factors. The growth levels in sectoral demand were estimated as ratios of 2050 to 2015 demands, where the growth estimates were 5.1, 3.8, 3.2, 1.3, and 1.4 in the building sector, electricity generation, heavy industries, residential sector, and agricultural residue burning, respectively. However, despite expanding sector-wise demands in both S2 and S3 scenarios, there is reduced energy consumption due to the adoption of clean energy technologies. Venkataraman et al. (2018) provide a detailed description of these scenarios.

In our study, we estimate the potential health benefits in terms of improvement in life expectancy and averted premature mortalities due to ischemic heart disease (IHD), cerebrovascular disease (CEV, stroke), chronic obstructive pulmonary disease (COPD), and lung cancer (LC) for the adult population, and acute lower respiratory illness (ALRI) for infants (< 5 years old) linked to
PM$_{2.5}$ exposure in the year 2030 that is achievable with the implementation of S2 and S3 scenarios with respect to the baseline scenario (BAU).

## 2 METHODS

### 2.1 Model Description

We have used the regional Weather Research and Forecasting model coupled with chemistry (WRF-Chem) v3.9.1 with MOZART-4 gas-phase chemistry and GOCART aerosol scheme. Since emissions are influenced much by regional factors, the WRF-Chem being a regional transport model has the advantage of resolving emissions at finer grid scales by considering the regional impacts of emissions. It also has the ability to simulate full coupling between chemistry and meteorology compared to the global model GEOS-Chem. Although both GEOS-Chem and WRF-Chem employ a bulk aerosol approach to represent aerosol processes, certain aerosol processes such as the ageing of aerosols, deposition parameterization, and parameterizations of online natural emissions (e.g., dust and sea-salt) are treated differently in WRF-Chem. The MOZART-4 gas-phase chemistry incorporates 84 gas-phase species, 39 photolysis and 127 gas-phase reactions, and 12 bulk aerosols compounds. The GOCART aerosol model simulates five major types of aerosols, e.g., sulfate, black carbon, organic carbon, dust, and sea salt. Anthropogenic emissions of CO, NO$_x$, SO$_2$, NMVOC, NH$_3$, PM$_{2.5}$, BC and OC are taken from the HTAP-v2 inventory (http://edgar.jrc.ec.europa.eu/htap_v2/) that consists of 0.1° × 0.1° grid maps using nationally reported emissions combined with region-specific inventories in the format of sector-specific grid maps for the year 2010. Details of the HTAP emission inventory can be found in Janssens-Maenhout et al. (2015). The simulations were run at a spatial resolution of 30 km × 30 km covering the Indian Subcontinent (0–40°N to 60–120°E) and 27 vertical levels from surface up to 50 hPa. We used the Thompson scheme (Thompson et al., 2008) to parametrize the cloud microphysical processes, the Grell 3D Cumulus Parameterization scheme (Grell and Dévényi, 2002) for cumulus parameterisation, the Bougeault and Lacarrere Planetary Boundary Layer (PBL) scheme (Bougeault and Lacarrere, 1989) for the boundary layer and Noah Land Surface Model (Chen and Dudhia, 2001) for providing heat and moisture fluxes over land. The short wave radiation was parameterized using the Goddard scheme (Chou and Suarez, 1994) and the Rapid Radiative Transfer Model (RRTM) (Mlawer et al., 1997) was used for the parametrization of long wave radiation. The aerosol-radiation feedback was allowed during the simulations. A summary of the physical and chemical parameterization schemes used in the model setup is given in Table 1. The performance of the model for simulating surface PM$_{2.5}$ concentration over India is provided in a number of previous studies (Ghude et al., 2013, 2016, 2020b; Jena et al., 2015a, 2015b; Kumar et al., 2015; Krishna et al., 2019; Kulkarni et al., 2020) and these studies are consistent with the ground-based and satellite measurements. Kumar et al. (2012) showed the index of agreement for key meteorological parameters to be greater than 0.6, highlighting the fidelity of WRF-Chem in simulating the variations around the

<table>
<thead>
<tr>
<th>Atmospheric Processes</th>
<th>Model Configuration</th>
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<tbody>
<tr>
<td>Microphysics</td>
<td>Thompson scheme</td>
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<tr>
<td>Shortwave radiation</td>
<td>Goddard</td>
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<tr>
<td>Longwave radiation</td>
<td>RRTM</td>
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<tr>
<td>Cumulus</td>
<td>Grell 3D Cumulus Parameterization scheme</td>
</tr>
<tr>
<td>Planetary Boundary layer</td>
<td>Bougeault and Lacarrere Planetary Boundary Layer (PBL) scheme</td>
</tr>
<tr>
<td>Surface Layer</td>
<td>Noah Land Surface Model</td>
</tr>
<tr>
<td>Gas-phase chemistry</td>
<td>MOZART-4</td>
</tr>
<tr>
<td>Aerosol chemistry</td>
<td>GOCART</td>
</tr>
<tr>
<td>Photolysis</td>
<td>Madronich F-TUV (Madronich, 1987)</td>
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<tr>
<td>Biogenic emissions</td>
<td>Megan (Guenther et al., 2006)</td>
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<tr>
<td>Fire emissions</td>
<td>NCAR version-1 (FINNv1) (Wiedinmyer et al., 2011)</td>
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<tr>
<td>Dry deposition</td>
<td>Wesely (1989)</td>
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<tr>
<td>Wet deposition</td>
<td>Neu and Prather (2012)</td>
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Table 2. Emission incremental factor for different pollutants.

<table>
<thead>
<tr>
<th>Air Pollutants</th>
<th>BAU (2030)</th>
<th>S2 (2030)</th>
<th>S3 (2030)</th>
</tr>
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<tbody>
<tr>
<td>BC</td>
<td>1.3</td>
<td>0.9</td>
<td>0.4</td>
</tr>
<tr>
<td>NOx</td>
<td>2.5</td>
<td>1.9</td>
<td>1.2</td>
</tr>
<tr>
<td>OC</td>
<td>0.8</td>
<td>0.7</td>
<td>0.3</td>
</tr>
<tr>
<td>CO</td>
<td>0.9</td>
<td>1.6</td>
<td>1.1</td>
</tr>
<tr>
<td>NMVOC</td>
<td>0.7</td>
<td>0.6</td>
<td>0.3</td>
</tr>
<tr>
<td>PM$_{2.5}$</td>
<td>1.7</td>
<td>1.3</td>
<td>0.5</td>
</tr>
<tr>
<td>SO$_2$</td>
<td>1.6</td>
<td>1.2</td>
<td>0.6</td>
</tr>
<tr>
<td>NH$_3$</td>
<td>1.3</td>
<td>1.2</td>
<td>1.1</td>
</tr>
</tbody>
</table>

observed mean. Ghude et al. (2016) showed the excellent capability of the model in capturing the seasonality of surface PM$_{2.5}$ over major sites in India, especially over the IGP region. Recent studies by Jena et al. (2021), Sengupta et al. (2022) and Ghude et al. (2022) demonstrate the efficacy of the WRF-Chem model with detailed performance statistics in capturing the variability of PM$_{2.5}$ concentration, simulation of meteorology w.r.t in-situ observations and in assisting the decision-makers in air quality management activities, respectively. However, the GOCART aerosol scheme used in the present simulation does not include nitrate and secondary organic aerosols in the simulated PM$_{2.5}$ concentration. The relative contribution of nitrate and SOA in PM$_{2.5}$ is about 10% and 15% in India (Behera and Sharma, 2010), adding about 3% and 5% uncertainty to the simulated PM$_{2.5}$ exposure. The model simulated hourly surface PM$_{2.5}$ concentrations at 30 km horizontal resolution covering the entire Indian sub-continent. We performed simulations for reference (BAU), aspirational (S2) and ambitious (S3) scenarios for the entire year of 2030. BAU, S2, and S3 emission scenarios for the year 2030 are derived from the HTAP anthropogenic emissions by scaling HTAP emissions with yearly scaling factors based on the projections given in Venkataraman et al. (2018) for India, which are shown in Table 2. Detailed information on emission projections and methods is presented in Venkataraman et al. (2018). For NH$_3$ emissions, we used projections based on RCP8.5 and RCP6.0 scenarios (Moss et al., 2010). All simulations are performed using meteorology and boundary conditions for the year 2018 based on National Centers for Environmental Prediction Final (GFS/FNL) meteorological reanalysis fields. In this study, we considered 2018 as the base year since this was the latest year with available meteorological data when the experiments were conducted. Spatially and temporally (6 hourly) varying climatological mean chemical boundary conditions were provided by the global model simulations from the Model for Ozone and related Chemical Tracers (MOZART-4) from 2007–2017 (Emmons et al., 2010).

2.2 Health Benefit Estimate

According to the Registrar General and Census Commissioner, Government of India, for the year 2011, around 31% of the residents are 0–14 years old, and 5% of the residents are above 65 years old. We scaled the 2011 population uniformly to project the count for 2030 but kept the same age grouping for the projected population in 2030. These population data are re-mapped to the 30 km model grid using GIS-based methodology. The premature mortality due to PM$_{2.5}$ exposure in 2030 has been estimated for BAU, S2 and S3 scenarios using the human health impact function described in Murray et al. (2020). Premature mortalities ($\Delta M$) were estimated (Eq. (1)) as a function of Population count ($P$) for the specific age category, the baseline mortality rate of a particular disease category $\delta c$ for India and attribution fraction ($(RR – 1)/RR$) for a specific relative risk (RR). Here we used State-specific baseline mortality for COPD, IHD and Stroke in India, which is based on an estimate reported in Chowdhury and Dey (2016).

$$\Delta M = \delta c \left( \frac{(RR – 1)}{RR} \right) P$$ (1)

The relative risk (RR) due to COPD, CEV, IHD, ALRI and LC related mortality associated with long term exposure to PM$_{2.5}$ concentrations is calculated using the integrated exposure-response function given in Murray et al. (2020). In the present study, the values of RR attributable to PM$_{2.5}$
exposure for IHD, CEV (stroke), COPD, and LC disease categories are calculated for the adults (25–95 year) population, and acute lower respiratory illness (ALRI) is calculated for infant population. IHD estimates were split into the 5-year age group of the adult population. We also estimated lower and upper limits of premature mortality associated with the above disease categories.

Using the simulated annual mean PM$_{2.5}$, the premature mortalities for five different diseases in the year 2030 under the scenarios BAU, S2 and S3 are estimated for the population in each model grid. The state and national level mortalities are estimated for the year 2030 by summing all grids within the state and national boundaries (Fig. S1) for each scenario. Finally, we estimated averted premature mortalities by calculating the decrement in mortalities under S2 and S3 with respect to the baseline scenario BAU. For calculating lost life expectancy due to PM$_{2.5}$ exposure, we followed the estimate described in Pope et al. (2009). As per their estimate, an increase of 1 µg m$^{-3}$ in PM$_{2.5}$ exposure decreases the mean life expectancy by about 0.061 ± 0.02 years. Using this relationship, state and national level lost life expectancy is estimated for the year 2030 under the BAU, S2 and S3 scenarios. Finally, the decrease in health burden in terms of improvement in life expectancy under S2 and S3 with respect to the baseline scenario is estimated.

### 3 RESULTS AND DISCUSSION

#### 3.1 Improvement in Ambient PM$_{2.5}$ Exposure under S2 and S3

Spatial pattern of simulated annual mean ambient PM$_{2.5}$ concentration in BAU scenario and for emission mitigation scenario S2 and S3 in 2030 are illustrated in Figs. 1(a), 1(b) and 1(c), respectively. Fig. 1(a) illustrates that the exposure to ambient PM$_{2.5}$ varies widely across India, the annual mean ambient PM$_{2.5}$ concentration for the BAU scenario exceeds the National Ambient Air Quality Standard (NAAQS) of 40 µg m$^{-3}$ (http://www.indiaenvironmentportal.org.in/files/file/Permissible%20Level%20for%20Pollutants.pdf) in most parts of India in 2030. Among the different regions, the Indo-Gangetic plain of India showed higher exposure to ambient PM$_{2.5}$ concentration with values as high as 120–130 µg m$^{-3}$ in the northwestern and northeastern regions of the Indo-Gangetic Plain (IGP). Figs. 2(a) and 2(b) show spatial patterns of the change in exposure to simulated ambient annual mean PM$_{2.5}$ concentrations in 2030 for S2 and S3 emission scenarios with respect to the BAU scenario, respectively. In the S2 scenario, all India mean surface PM$_{2.5}$ concentration exposure decreases from about 63 ± 23 µg m$^{-3}$ to 54 ± 18 µg m$^{-3}$, i.e., by about –9 µg m$^{-3}$ (15%), with respect to the BAU scenario. In most parts of India, exposure to annual mean PM$_{2.5}$ concentration decreases by about 5–15 µg m$^{-3}$, whereas regions of northeastern and western India exhibit a decrease of about 20–30 µg m$^{-3}$ (Fig. 2(a)). Despite these decreases, the annual mean ambient PM$_{2.5}$ concentration in most regions of India exceeds NAAQS, maintaining similar high concentrations over IGP (Fig. 1(b)). However, simulations show that pockets of exceedingly high ambient annual mean PM$_{2.5}$ concentration (> 100 µg m$^{-3}$) reduced significantly to smaller levels in the north-western and northeastern regions of IGP. It indicates that achieving the S2 emission scenario in 2030 would result in only modest improvement in high levels of PM$_{2.5}$ exposure with respect to the BAU scenario. The estimated values of exposure to ambient PM$_{2.5}$ concentration in our study under the BAU and S2 scenarios are found to be consistent with Venkataraman et al. (2018). They have shown an increase in all India PM$_{2.5}$ concentration to 160 µg m$^{-3}$ i.e., a 62.37% increase in REF scenario and modest improvement in S2 scenario w.r.t 2015 (base year considered in Venkataraman et al. (2018)) using the GEOS-Chem model. Modest expansion of renewable energy (40%) in power generation, a modest increase in energy efficiency in industries, slower shifts to BS-VI standards in the transport sector, and a slow shift to energy-efficient technologies and fuels for residential purposes have resulted in moderate improvement in the air quality in the S2 scenario keeping the overall annual mean ambient PM$_{2.5}$ concentration in most regions of India above the NAAQS. The north-western and north-eastern states of the IGP are quite densely populated and hence, adoption of the aspirational policies under the S2 scenario has larger implications on these states which consequently results in a significant decrease in the ambient PM$_{2.5}$ concentration in these states w.r.t the rest of the country.

If the emissions are mitigated as per the S3 scenario, then all India mean surface PM$_{2.5}$ concentration is estimated to be 32 ± 11 µg m$^{-3}$, which results in a significant decrease of about 49% (–31 µg m$^{-3}$) in PM$_{2.5}$ exposure with respect to BAU scenario. In most parts of India,
Fig. 1. Spatial pattern of the simulated annual mean ambient PM$_{2.5}$ concentration in 2030 under (a) BAU (b) S2 and (c) S3 scenario.

Simulations with the S3 scenario reveal a significant drop (about 25–45 $\mu$g m$^{-3}$) in ambient annual mean PM$_{2.5}$ exposure with respect to the BAU scenario (Fig. 2(b)), except in the Indo Gangetic Plain where it indicates even a larger drop of PM$_{2.5}$ exposure of about 50–70 $\mu$g m$^{-3}$. Venkataraman et al. (2018) also showed that significant reductions in PM$_{2.5}$ exposure are achievable in 2030 in the S3 scenario. Under the S3 scenario, simulated air quality is also projected to improve relative to the S2 scenario. Fig. 2(c) demonstrates a spatial pattern of the change in annual mean PM$_{2.5}$ concentrations if the ambitious scenario (S3) is followed instead of the aspirational (S2) emission scenario. Fig. 2(c) follows the similar spatial pattern as that of Fig. 2(a) but with more reduction in PM$_{2.5}$ exposure in northern, north-eastern, and north-western regions, and the magnitude of a dip in PM$_{2.5}$ exposure between S2 and S3 is found double than between BAU and S2. This implies that the implementation of the S3 scenario in 2030 is expected to yield a significant improvement in air quality relative to the BAU scenario. Adoption of aggressive policies attributes to the significant improvement in the ambient PM$_{2.5}$ exposure in the S3 scenario in comparison to the S2 scenario. Expansion of 75–80% of non-fossil-power generation in the power sector, a near-complete shift to high-efficiency industrial technologies, a large shift to public vehicles and increased share of electric and CNG vehicles, aggressive shifts to LPG, electricity, and solar energy
for residential activities and a slow shift (35% phase-out by 2030) towards mitigating agricultural residue burning resulted in significant improvement in the ambient air quality in the S3 scenario. Again, since the population density in the states of the IGP region is quite high w.r.t the rest of the country, shifting to cleaner energy and more sustainable modes of development in the S3 scenario would affect a larger population thus resulting in a substantial reduction in the PM$_{2.5}$ exposure in these states. Fig. 1(c) illustrates that although the PM$_{2.5}$ exposure is below 40 µg m$^{-3}$ in the southern region of India in the S3 scenario, the central, north-eastern, and north-western regions still do not meet the NAAQS.

To illustrate the state-wise pattern of PM$_{2.5}$ exposure for BAU, S2 and S3 scenarios, we present bar charts showing annual mean ambient PM$_{2.5}$ exposure and change in annual mean ambient PM$_{2.5}$ in S2 and S3 relative to BAU scenario in Figs. 3(a) and 3(b), respectively. Similarly, Fig. 4 shows a state-wise percentage of PM$_{2.5}$ exposure above or below NAAQS under the BAU, S2 and S3 scenarios. Under the BAU scenario, in 2030, the annual mean PM$_{2.5}$ exposure in most of the
Indian states is above NAAQS, except for north-eastern states (Sikkim and Arunachal Pradesh) and Himalayan states (Jammu and Kashmir, and Uttarakhand). Out of twenty-nine states, five states fall below the NAAQS and the exposure to ambient PM$_{2.5}$ concentrations in these states would be 5–50% lower relative to NAAQS (Fig. 4(c)). In six states, exposure to ambient PM$_{2.5}$ concentrations stands 3–25% above NAAQS and for the remaining 18 states, the exposure is 50–190% above NAAQS. Delhi ranks highest on the list (117 µg m$^{-3}$) with ~2 times higher exposure followed by West Bengal (100 µg m$^{-3}$) and Bihar (97 µg m$^{-3}$) with ~1.5 times higher exposure relative to NAAQS. The population of the five states (having PM$_{2.5}$ exposure below NAAQS), is quite lower than the maximum of the other 22 states with PM$_{2.5}$ exposure above the NAAQS. Since the Indian national emissions of primary PM$_{2.5}$ are dominated by residential sectors, therefore, anthropogenic emissions would be more from states with higher populations and hence cause higher pollution in their immediate vicinity at the state level. Secondly, in terms of geographical location, the states in the IGP region have higher PM$_{2.5}$ concentrations as compared to other states owing to the blockage of wind circulations by the Himalayas, which results in the trapping of polluted air over these states. The southern states, experiencing a larger share of coastal areas, have lower PM$_{2.5}$ pollution due to relatively enhanced wind flow in terms of land and sea breezes, which disperses emissions considerably.
Even if the S2 scenario is achieved in 2030, most states do not meet the NAAQS. However, in S2 scenario, six more states would rank below the NAAQS, and in five states, exposure to high ambient PM$_{2.5}$ would fall in the range between 3–25% above NAAQS. Slower shifts to the use of cleaner, energy-efficient technologies in industries, transport, and residential sectors, a moderate share of renewable energy in power sectors, and the absence of any strict policy in reducing the agricultural residue burning, can be attributed to the moderate improvement in the ambient air quality in the S2 scenario keeping a majority of states still above the NAAQS. As a result, with the S2 scenario, 21% of additional states in India would meet the NAAQS, and overall, 38% of states would remain below the NAAQS with exposure 5–55% lower relative to NAAQS (Fig. 4(b)). Our estimates are consistent with findings of Venkataraman et al. (2018), wherein they have also projected significant increases in PM$_{2.5}$ concentration w.r.t. present-day values under REF and S2 scenarios in many states of the IGP region such as Bihar, Haryana, Jharkhand, Uttar Pradesh, Orissa, West Bengal.

Further, pursuance to achieving the S3 emission mitigation scenario ambitiously in 2030 would lower the exposure to ambient PM$_{2.5}$ concentration below NAAQS in 17 more states (~59% states) relative to BAU. In the S3 scenario, the exposure would fall more towards the lower side in 38% of states (Fig. 4(a)), where exposure to ambient PM$_{2.5}$ concentrations would fall 10–65% lower relative to NAAQS. This implies a significant improvement in ambient air quality in these states compared to other states which fall below NAAQS under the S3 scenario. However, even by pursuing the S3 scenario, eight states in India would continue to violate NAAQS. Of these eight states, PM$_{2.5}$ exposure would remain 37% above NAAQS in Delhi, and in the remaining seven states, exposure to high ambient PM$_{2.5}$ would fall in the range of 1–15% above NAAQS. Similar to the estimates of REF and S2 scenarios, these estimates are again consistent with that of Venkataraman et al. (2018) wherein they have projected the majority of states and union territories to fall below the NAAQS except for Delhi and other 9 states in the S3 scenario.

### 3.2 Health Benefits under S2 and S3 Scenarios

In a recent study by Pandey et al. (2021), it is found that nearly 1.67 million deaths i.e., 17.8% of the total deaths in India were attributable to air pollution in 2019. The majority of the deaths were from ambient particulate matter pollution (~0.98 million) and household air pollution (~0.61 million). Although the death rate due to household air pollution decreased by 64.2% in a span of thirty years (i.e., from 1990 to 2019), the death rate due to ambient particulate matter pollution increased by 115.3%. Therefore, the high burden of death and diseases due to the degrading air quality as highlighted in Pandey et al. (2021) has encouraged us to look into the health benefits achievable by 2030 in India by adopting the policies under S2 and S3 scenarios. We have assessed the health benefits of implementing aspirational (S2) and ambitious (S3) scenarios by estimating averted excess mortalities and improved life expectations across India with respect to BAU. We have estimated excess numbers of mortalities using the integrated exposure-response function (Eq. (1) for each scenario S2 and S3) and averted mortalities are calculated by subtracting S2 and S3 excess mortalities from those of BAU. We further estimated the health burden in terms of life years lost due to PM$_{2.5}$ exposure for each scenario following the estimates given in Pope et al. (2009) and used in Ghude et al. (2016). Improved life expectancy across India is calculated by subtracting life years lost from the BAU scenario. The averted numbers of excess mortalities in 2030 due to ambient PM$_{2.5}$ exposure in the S2 and S3 scenarios for different health outcomes across India are summarized in Table 3. Pandey et al. (2021) have shown that of the total deaths attributable to air pollution in India in 2019, the largest proportions were due to COPD (32.5%) and IHD (29.2%), followed by stroke (16.2%) and lower respiratory infections. Our results show that reducing all India PM$_{2.5}$ exposure by about 15% under the S2 scenario would prevent ~274,000 (8.3%) nationally aggregated total excess mortality burden with a 95% confidence interval of 301,000–237,000. For adults (age > 25 years), all India avoided excess mortalities linked to IHD, CEV (stroke), COPD, and LC are estimated to be about 78,000 (95%CI: 93,000–60,000), 76,000 (95%CI: 82,000–64,400), 118,000 (95%CI: 125,000–110,000), and 400 (95%CI: 117–600) people, respectively. Avoided mortalities of ALRI for children < 5 years old are estimated about 1,400 (95%CI: 1120–1500). Nationally, under the S2 scenario, reduced ambient PM$_{2.5}$ exposure is estimated to improve all India mean life expectancy by about 0.6 ± 0.2 years.
Table 3. Averted numbers of excess mortalities in 2030 due to ambient PM$_{2.5}$ exposure under S2 and S3 scenario for different health outcomes across India.

<table>
<thead>
<tr>
<th>Health Endpoints</th>
<th>BAU-S2 (LB-UB)</th>
<th>BAU-S3(LB-UB)</th>
</tr>
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<tbody>
<tr>
<td></td>
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</tr>
<tr>
<td>IHD*</td>
<td>78,000 (93,000–60,000)</td>
<td>268,000 (300,000–211,000)</td>
</tr>
<tr>
<td>CEV (stroke)*</td>
<td>76,000 (82,000–64,400)</td>
<td>245,000 (256,000–210,000)</td>
</tr>
<tr>
<td>COPD*</td>
<td>118,000 (125,000–110,000)</td>
<td>258,000 (257,000–260,000)</td>
</tr>
<tr>
<td>LC*</td>
<td>400 (117–600)</td>
<td>1200 (815–1600)</td>
</tr>
<tr>
<td>ALRI*</td>
<td>1,400 (1120–1500)</td>
<td>3600 (2900–3900)</td>
</tr>
<tr>
<td>Total</td>
<td>274,000 (301,000–237,000)</td>
<td>775,000 (820,000–688,000)</td>
</tr>
</tbody>
</table>

*For adult population (> 25 years old).

For infants (<5 years old).

Following the S3 scenario would drop all India ambient PM$_{2.5}$ exposure by 49% which would prevent a total of 775,000 (~23.6%) excess mortality burden with a 95% confidence interval, 820,000–688,000. Compared to the S2 scenario, the S3 scenario would potentially reduce nationally integrated annual excess mortalities estimate by 501,000 people. Averted mortalities linked to IHD, CEV (stroke), COPD, LC and (ALRI) are estimated to be about 268,000 (95%CI: 300,000–211,000), 245,000 (95%CI: 256,000–210,000), 258,000 (95%CI: 257,000–260,000), 1200 (95%CI: 815–1600), and 3600 (95%CI: 2900–3900) people, respectively. On the other hand, improvement in all India mean life expectancy in the S3 scenario is estimated to be about 1.9 ± 0.7 years, which is about 1.3 years more than that of the S2 scenario.

The avoided mortalities for different respiratory disease categories and improvement in life expectancy across different states of India estimated for S2 and S3 scenarios relative to BAU are shown in Figs. 5(a), 5(b) and 5(c), wherein a pattern similar to changes in state-wise ambient PM$_{2.5}$ exposure is seen (Fig. 3). Highlighting the concern related to ambient particulate matter pollution, Pandey et al. (2021) showed that 11.5% of the total disability-adjusted life years (DALY) rate in 2019 was attributable to air pollution with the highest rates in several northern states of India. However, our study ignites the hope indicating a substantial improvement in averted mortalities and life expectancy that is achievable with the implementation of aspirational and ambitious regulations under the S2 and S3 scenarios, respectively. State-wise highest number of averted mortalities under S2 and S3 scenarios is seen in Bihar (BR) (S2:1 04,000, S3:142,800), followed by West Bengal (WB) (S2:46,400, S3:80,500) and Uttar Pradesh (UP) (S2:27,000, S3:135,000). In terms of life expectancy, the highest benefits are seen in Delhi which shows 1.3 years and 3.8 years increase in life expectancy for S2 and S3 scenarios, respectively. Similarly, increase in life expectancy for West Bengal (WB) under the S2 and S3 scenarios were 1.2 and 3.5 years, respectively, and that for Bihar in S2 and S3 scenarios were 1.3 and 3.4 years, respectively. In 70% of states, life expectancy would increase by 0.5 years and 1.5 years in 2030 under the S2 and S3 scenarios, respectively.

4 CONCLUSIONS

The present study evaluates the improvement in the air quality and subsequent health benefits that could be achieved due to a reduction in ambient PM$_{2.5}$ exposure in 2030 under the adoption of promulgated regulations (S2) and ambitious prospective regulations (S3) relative to business-as-usual (BAU) industrial and economic growth. Improvement in ambient air quality is evaluated by estimating the decrease in annual mean ambient PM$_{2.5}$ exposure and the number of states that meet the annual mean NAAQS of 40 µg m$^{-3}$ under S2 and S3 emission pathways. Health benefits are calculated by estimating number of averted excess mortalities and improvement in life expectancy. Achieving the S2 emission scenario in 2030 instead of BAU could result in a modest 15% (9 µg m$^{-3}$) decrease in all India ambient PM$_{2.5}$ exposure. Out of 29 states, 38% of states would meet the NAAQS with exposure lowered by about 5–55% relative to NAAQS. Modest improvement in air quality under the S2 scenario would avoid 8.3% (~274,000 persons) of nationally aggregated total excess mortality burden and improve life expectancy by ~0.6 years as compared with BAU emission pathways. On the other hand, pursuing S3 emission pathways...
Fig. 5. Avoided mortalities for different disease category in 2030 for (a) S2 and (b) S3 emission scenarios with respect to BAU. (c) Improvement in life expectancy across different states of India for S2 and S3 scenarios relative to BAU.
can result in a much larger decrease of about 49% (32 $\mu g m^{-3}$) in all India ambient PM$_{2.5}$ exposure. In 59% of states, annual PM$_{2.5}$ exposure would meet the NAAQS. Despite this, eight states in India under the S3 scenario would continue to have exposure above NAAQS. However, ambient PM$_{2.5}$ would fall in the range of 1–15% above NAAQS in seven of these states and in Delhi it would be 37% above NAAQS. In terms of health benefits, a significant improvement in ambient air quality would result in avoiding 23.3% (755,000 persons) of all India excess mortalities and an increase in life expectancy by about 1.9 years. This implies that the reduction in ambient PM$_{2.5}$ exposure is relatively larger than the reduction in associated excess mortality burdens. It is important to note that 15% and 49% reductions in all India ambient PM$_{2.5}$ exposure for the S2 and S3 scenarios lead to 8.3% and 20.3% decreases in excess mortalities, respectively. Overall, our results suggest that adopting promulgated regulations (S2) would result in a modest improvement in ambient air quality and noticeable health benefits in 2030. In contrast, adopting ambitious prospective regulations (S3) would significantly improve air quality (meeting NAAQS in many states), resulting in moderate health benefits.

It is to be noted that the estimated improvement in PM$_{2.5}$ exposure, life expectancy and averted premature mortalities are subject to several sources of uncertainty, including uncertainties in the model parameterizations and exposure-response functions. Additionally, the variability in emissions for South Asia adds some uncertainty (~30%) in the PM$_{2.5}$ emissions (Kurokawa et al., 2013), resulting in ~12% uncertainty in the estimated premature mortalities due to PM$_{2.5}$ exposure (Ghude et al., 2016). Besides, the GOCART aerosol model used in the present study does not include nitrate and secondary organic aerosols, which gives rise to uncertainties in the simulated PM$_{2.5}$ exposure. Uncertainty may also be due to the assumptions used in population projection and the mortality estimates. It should be noted that the present study does not focus on estimating premature mortalities from the individual source sectors and associated policy implications on particulate matter pollution across different states in India in 2030. Therefore, the future prospect of the present study lies in conducting higher-resolution simulations with a more explicit aerosol model that includes nitrates and the formation of SOA (as performed by Debnath et al. (2021)), thus addressing the uncertainty in the simulated PM$_{2.5}$ concentration to an extent. It will be also worth exploring the implications of individual sectoral policy implementations in 2030 across different states of India. Despite the limitations, this study highlights that a reduction in the PM$_{2.5}$ exposure over regional to urban scale in India, an increase in the number of averted mortalities, and an improvement in life expectancy by the year 2030 are achievable. It is worth noting that ambitious actions beyond the prospective regulations are warranted to achieve the major health benefits.

The findings in this study could be potentially beneficial to the pollution control authorities such as the central and state pollution control boards, Niti Aayog, and the Ministry of Environment and Climate Change (MoEFCC) in planning the implementation of strategic policies to mitigate air pollution and public health risk in different parts of India. The results might be helpful for the central government, state governments, and municipal corporations to allocate sufficient funding towards implementing the policies under the NCAP, thus leading to achieving the SDG targets. Additionally, the environmental ministry should also take initiatives toward developing a detailed emission inventory at national, state, and city levels to support air-quality management. Air pollution control in India should be treated as an essential investment. The existing efforts to mitigate air pollution should be further strengthened to foster the country’s future economic growth.

ACKNOWLEDGMENTS

We thank the Director, IITM, for his encouragement in carrying out the research work. We acknowledge the use of the WRF-Chem preprocessor tools provided by the Atmospheric Chemistry Observations and Modeling Laboratory (ACOM) of NCAR. This material is based upon work supported by the National Center for Atmospheric Research, which is a major facility sponsored by the National Science Foundation under Cooperative Agreement No. 1852977. The WRF-Chem model simulation was carried out on the HPC System ‘Aditya’ at IITM, India. We would like to thank Prof. Michael Brauer, Institute for Health Metrics and Evaluation, University of Washington for his kind assistance in providing the updated data for the calculation of Relative
Risk used in this study (Global Burden of Disease Collaborative Network. Global Burden of Disease Study 2019 (GBD 2019) Particulate Matter Risk Curves. Seattle, United States of America: Institute for Health Metrics and Evaluation (IHME), 2021, https://doi.org/10.6069/KWHW-2703). Supplementary data contains model mean data and all results for the Indian state per scenario. This work was supported by the National Supercomputing Mission (NSM) program grant to the authors at C-DAC (SK and DMC) and we are grateful to the Executive Director and the Director General of C-DAC. The authors would sincerely thank the anonymous reviewers and the editor of the journal for their insightful comments and valuable suggestions.

SUPPLEMENTARY MATERIAL

Supplementary material for this article can be found in the online version at https://doi.org/10.4209/aaqr.220112

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