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Air quality benefits from mitigation of Black Carbon emissions in Northern India

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Abstract

Ambient air pollution is now recognised as the highest health risk factor in India. The entire Indian population lives in areas with $PM_{2.5}$ levels exceeding the latest WHO annual Air Quality Guidelines 2021 (AQG) of 5 µg/m^3. One of the strong light-absorbing components of $PM_{2.5}$ is Black Carbon (BC) particles, which are released into the atmosphere from incomplete combustion. They can perturb the Earth's energy balance by absorbing solar radiation and modifying cloud microphysics, thereby contributing to global climate warming. BC emissions from India are among the highest globally, impacting the Indian summer monsoon, regional climate, and human health. While, from an economical and strategic policy intervention standpoint, BC particles are well suited for achieving co-benefits for both climate and public health. In addition, North India frequently suffers from extreme seasonal haze pollution. However, a complete understanding of the role of BC in amplifying pollution is still lacking. In this view, we attempt to assess the effectiveness of existing and planned air pollution control strategies in improving air quality in India. We compare alternate policy scenarios using the Greenhouse Gas-Air Pollution Interactions and Synergies -South Asia (GAINS) model framework with the baseline scenario reflecting the successful implementation of current legislation. We find that at present, the current emissions control measures aren't stringent enough to improve the air quality in Northern India. While, even with the most advanced control measures (i.e. in the Net Zero scenario) combined with stringent policy enforcements, the future $PM_{2.5}$ concentrations do not meet the latest WHO 2021 AQG for Northern India. The changes in meteorological parameters (like 2m temperature, wind speed and planetary boundary layer), detrimental to the dispersion of pollutants and haze formation show sensitivity towards changes in emissions reductions. Sustainable development and the Net Zero scenario are examples of the ambitious policies needed to achieve maximum air quality benefits in India. They potentially could be even more efficient if the role of BC in the formation of haze is better understood.

About the author

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Introduction

Globally, air pollution caused 6.7 million deaths in 2019, with exposure to outdoor particulate matter (PM) pollution responsible for over 4 million deaths (HEI, 2022). Both short-term (days to weeks) and long-term (months to years) exposure to air pollution can lead to major risk factors for premature mortality and morbidity from a wide range of non-communicable diseases (Cohen et al., 2017; Lelieveld et al., 2015). In light of this, World Health Organisation has identified air pollution as the largest environmental risk to public health worldwide. For India, ambient air pollution is now recognized as a leading health risk factor, with a growing body of evidence indicating associations between exposure to fine $PM_{2.5}$ (particulate matter having an aerodynamic diameter smaller than 2.5 microns), and increased health risks and premature deaths (Murray et al., 2020; Pandey et al., 2021; Stanaway et al., 2018). Recent literature shows air pollution was responsible for over 1.67 million premature deaths in India, of which nearly 1 million deaths were attributable to outdoor air pollution exposure (HEI, 2022). According to the latest estimates by the Health Effect Institute, 100% of the Indian population is exposed to fine particulate matter $PM_{2.5}$ levels exceeding the WHO annual Air Quality Guidelines for clean air. The already disproportionate high mortality and disease burden due to air pollution in India are even greater for some regions of broader North India (Balakrishnan et al., 2019). Besides the health threats, air pollution also accounts for economic losses and is estimated to be significantly high for India (a total loss of US $36·8 billion) with the highest per-capita losses in some major North Indian states in 2019 (Pandey et al., 2021). The population of India is estimated to increase by 31% by 2030 compared to 2015, with an increase of nearly ten times in Gross Domestic Product (expressed as GDP per capita) by 2050, according to a study by Purohit et al. 2019. Air pollution, therefore, poses a major challenge for India in achieving crucial sustainable development goals.

India ranks among one of the largest emitters of anthropogenic aerosols[1] in the world (Lu et al., 2011). These high emissions contributions from India are dominantly composed of sulfate and carbonaceous aerosols, driven by increased demand for energy in the last decade (Lu et al., 2011). Historically, residential sector contributions dominated the total emissions of Carbon monoxide (CO), $PM_{2.5}$, Black carbon (BC), Organic Carbon (OC) and non-methane volatile organic compounds (NMVOCs) until 2010 (Li et al., 2017). Furthermore, India also

[1] aerosols are fine solid and/or liquid particles suspended in the air with diameters in the range up to a few micrometers (Hinds,1999)

shows a continuous increasing trend in air pollutant emissions throughout 1950 – 2015, with increased contributions from transport and power plant sectors according to the most recent Asian emissions estimates by Kurokawa & Ohara (2020). This increasing trend over the last few decades in India has been attributed to cumulative consequences of rapid economic growth, population increase, lax emissions control measures and a dramatic rise in the construction of new power plants (Garg et al., 2001, 2006; Kurokawa & Ohara, 2020; Li et al., 2017).

However, recent estimates by McDuffie et al. (2020) observed a declining emissions trend for BC and OC from residential and informal industry sectors in India, a trend expected to continue for India with cleaner residential fuel policies in place (such as the Ujjawala scheme; http://www.pmujjwalayojana.in/). In comparison, BC emissions from the on-road transport sector are expected to rise (McDuffie et al., 2020; Venkataraman et al., 2018). There is a clear regional structure in the high emissions and resulting pollutant concentrations over Northern India, which is shown by an abundance of in situ monitoring data, chemical-transport modelling and satellite observation studies (Gadhavi et al., 2015; Venkataraman et al., 2018). The Indo-Gangetic plain (IGP) in Northern India, covering parts of Pakistan and Bangladesh, is widely known as a hotspot for heavy aerosol loading throughout the year (Mhawish et al., 2020). It is a region characterised by a dense population, intensive multi-cropping system and rapid industrialisation. The strong seasonal emissions from the IGP region often lead to intense haze and smog conditions over broader North India and the downwind regions (Mhawish et al., 2022; Ramachandran et al., 2020; Roozitalab et al., 2020).

Black Carbon (BC) is fine particulate matter's light-absorbing component (Lack & Cappa, 2010). BC, often known as soot, is released during incomplete combustion of carbon-containing fuels like coal, oil and gas, or biofuels like wood, agricultural residues and forest and vegetation fires. BC aerosols are short-term climate forcers with a net positive radiative forcing (Bond et al., 2013; Jacobson, 2001). BC emissions from India are among the highest globally and significantly impact the Indian summer monsoon, regional climate, and human health (Bond et al., 2013; Ramanathan et al., 2001; Wang et al., 2014). Globally, Asia has been found to emit 60% of the total anthropogenic emissions, with a dominant contribution from the residential sector (Klimont et al., 2017). As presented in Figure 1, independent estimates by Paliwal et al. (2016) show that the domestic fuel sector contributes to about

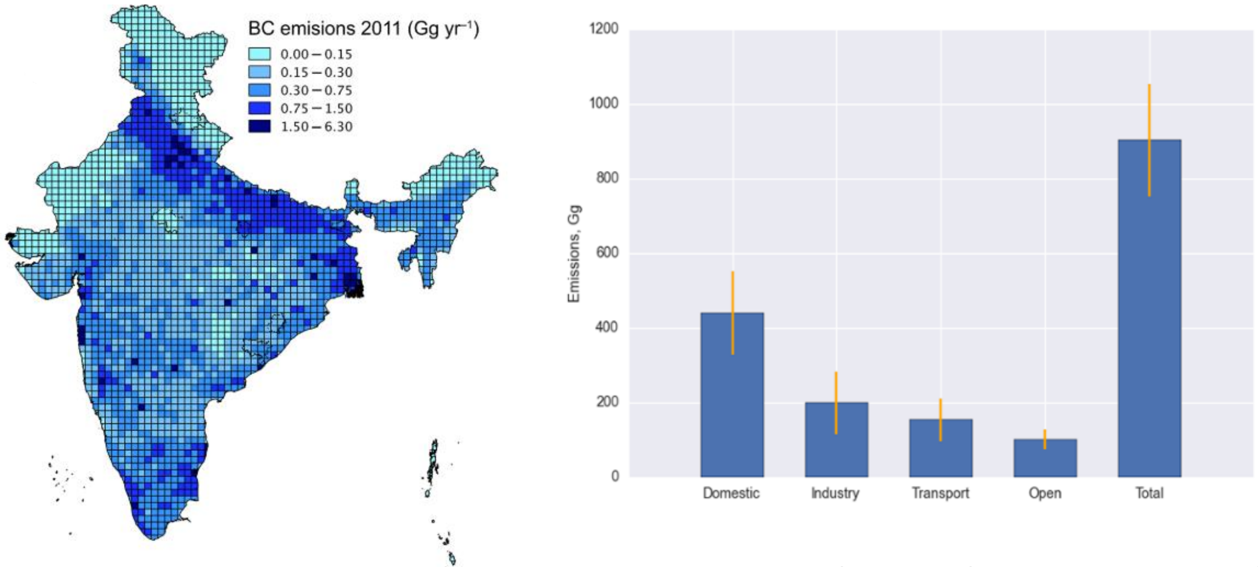

Figure 1. Spatial distribution of total BC emissions (Gg/yr) for India for the year 2011 (left panel) and Mean and standard deviation for each of the major emission sectors in India for the year 2011 (right panel) (Source: Paliwal et al., 2016)

47% of BC emissions in India in 2011. Consequently, mitigation of domestic sources by designing clean household fuel policies could offer nationwide benefits in terms of air quality and population exposure (Chowdhury et al., 2019). Furthermore, control of BC emissions offers a potential scope for achieving co-benefits for climate and public health (Harmsen et al., 2020; Menon et al., 2002).

In addition, North India frequently suffers from extreme seasonal haze pollution. Recently, significant aerosol-planetary boundary layer (PBL) feedbacks have been reported to impact the vertical temperatures and the PBL stability over China during extreme haze events (Ding et al., 2016). PBL can be defined as the physically mixed layer which allows for horizontal mixing and dilution of pollutants and is impacted by changes in vertical temperature in the atmosphere. Aerosol-PBL feedbacks are thought to influence the vertical temperature profile (stabilising it) significantly and consequently increase surface pollutant concentrations during haze episodes. Such feedbacks have previously been found to induce heating in the upper PBL and enhance near-surface haze pollution over China (Ding et al., 2016; Huang et al., 2018; Su et al., 2020). However, a complete understanding of the role of BC in amplifying pollution over broader Northern India is still lacking. Therefore, there is a critical need to assess the current particulate matter haze pollution situation and the future air quality concerning the evolution of such intense events in Northern India.

This study looks at future BC emissions reductions from a policymaking context and the potential co-benefits in mitigating severe haze pollution. In recent years, the Indian

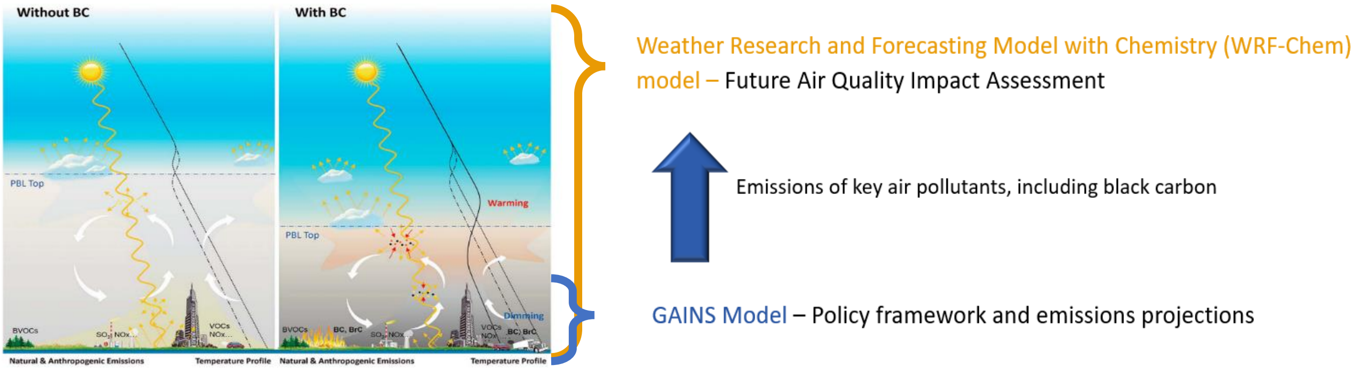

Figure 2. Left: The hypothesized mechanism for aerosol-boundary layer feedback loop over an urban region depicting different BC emission scenarios. Without BC conditions on the right depicts more BC sources and the colour difference between the two panels highlights the differences in the chemical composition of the respective urban plumes. The framework on the right describes the tools used in this study which address different components of the high air pollution issue

government has been making national and state-level efforts to control local and transboundary air pollution. One of the efforts has been to reduce $PM_{2.5}$ and PM_{10} levels by 20-30% by 2024 compared to 2017 levels in 122 cities under the National Clean Air Program 2019 (NCAP Tracker, 2019). However, stricter control measures and overcoming the challenge of political will is necessary to curb India's air pollution issue. The effective policies need to be economically feasible and, at the same time, should maximise the air quality benefits by being scientifically robust. Given the close and complex interplay between environment and economics, it is crucial to investigate the implications of growth in the economy and the evolution of emissions in India for future air quality. We evaluate baseline and alternative policy scenarios using the Greenhouse Gas-Air Pollution Interactions and Synergies (GAINS) model (Amann et al., 2011) and combine them with the chemistry transport modelling results. The modelling tools are used to quantify the role of emissions and pollutant-meteorology interactions as the drivers of future air quality in India. BC's role in forming new particles and promoting severe haze episodes has not been quantified in the Indian context so far. The GAINS anthropogenic emissions are used to drive the high-resolution atmospheric chemistry transport modelling for the base year 2018 and the year 2030. We study the scenarios (described in the next section) using the GAINS model and present the preliminary modelling results for the base year 2018 and target year 2030 in this report.

Data and Methods

GAINS model and Scenario definitions

For future emissions and policy implementation framework, we study a reference (also referred to as the baseline) scenario with current and planned air pollution control policies and alternate scenarios with varying degrees of stricter control policies and activity pathways. The integrated assessment framework of the GAINS model implemented for India (Purohit et al., 2010) is used for this purpose. In this study, we have analysed three alternative policy scenarios, briefly defined in Table 1. As a baseline for the further evolution of the drivers of pollution, this report adopts the trends of emission generating socio-economic activities (i.e., population growth, economic development, energy consumption, industrial activities, agricultural production) that have been published by the International Energy Agency (IEA) in its World Energy Outlook 2021 (IEA-WEO, 2021). The first part of this work looks at the following four scenarios, which are developed in the context of future socio-economic developments and decarbonisation targets for India:

1) **Baseline or current legislation (Base-CLE)**

   The baseline scenario reflects current policy settings based on a sector-by-sector assessment of the specific policies that are in place, as well as those that have been announced by the government (i.e., nationally determined contributions). This scenario considers the successful and efficient implementation of current and planned air pollution control policies, measures and legislations.

2) **Baseline scenario With Maximum Feasible Reductions (Base-MFR)**

   The Base-MFR scenario represents an alternate future air quality scenario wherein all potential benefits are completely achieved from fully implementing the most advanced emission control technologies. The Base-MFR scenario assumes the best technological measures in place in future which could be improved upon under economic incentives, and it does not consider cost constraints.

3) **Net zero emissions scenario with maximum feasible reductions (NZE-MFR)**

   This is a normative IEA scenario and consistent with limiting the global temperature rise to 1.5 °C without a temperature overshoot (with a 50% probability), in line with reductions assessed in the IPCC in its Special Report on Global Warming of 1.5 °C. NZE-MFR scenario adopting MFR control measures for air pollution control.

4) **Sustainable Development Scenario with maximum feasible reductions (SDS-MFR)**

   The SDS-MFR scenario lays out integrated response strategies to limit the global temperature increase to 2°C by the end of 2100. The strategies include measures such as adopting MFR control measures and additional emission control measures for non-industrial sources (e.g., access to cleaner and efficient cooking, pavement of roads and effective ban on crop residue and solid waste burning). The SDS-MFR scenario assumes an internationally agreed stringent policy framework to mitigate climate change (SDG-13), improve air quality (SDG-3) and ensure universal access to clean energy (SDG-7).

More details about the activity data and policies in these scenarios in the GAINS framework can be found elsewhere (Dimitrova et al., 2021; Purohit et al., 2019; IEA-WEO,2021; Rafaj et al., 2018).

Table 1. Definition of the scenarios formulated for the study

Scenarios	**Name**	**Description**
a) Baseline/Current Legislation Scenario (2018)	Base-CLE	Current emissions control legislation implemented in 2018
b) Baseline scenario with maximum feasible reductions	Base-MFR	Maximum feasible emissions reduction from full implementation of advanced control technologies
c) Net zero emissions scenario with maximum feasible reductions	NZE-MFR	Sets ambitious targets for Net Zero CO_2 emissions from global energy sector
d) Sustainable Development Scenario with maximum feasible reductions	SDS-MFR	Integrated policy measures to achieve climate change, air quality and modern energy access objectives

Method- WRF-Chem Simulations

To assess future air quality, we design modelling experiments using the Weather Research Forecasting with Chemistry model (WRF-Chem v4) (Grell et al., 2005) simulations and evaluate the changes in $PM_{2.5}$ and BC concentrations in the present-day and future scenarios. WRF-Chem model allows for highly resolved Spatio-temporal distribution of major pollutants simultaneously with meteorology (Grell & Freitas, 2014). Since regional air quality modelling is computationally intensive, we select one- week period of high pollution period in the post-monsoon season for comparison between scenarios. The model is run at a high spatial resolution of 12 x 12 km for the years 2018 and 2030 for this study. The comparisons from alternate scenario, NZE-MFR (2030), are presented in this work. The smoke and fire from crop residue burning in Northern India leads to severe air pollution conditions locally and in the downwind regions of Northern Indian states during October-November. The gridded

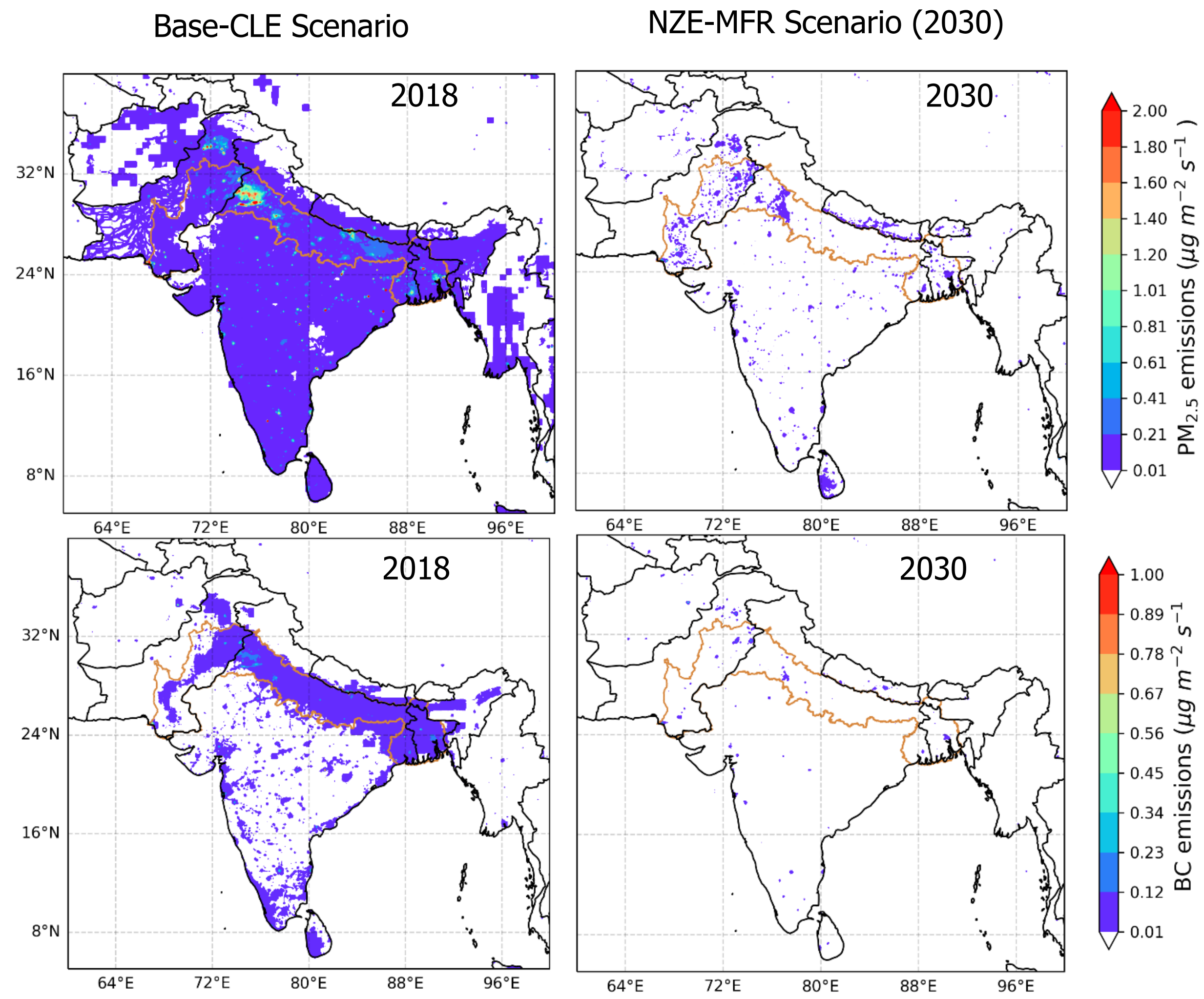

Figure 3. Mean anthropogenic emission inputs in WRF-Chem for $PM_{2.5}$ (upper panel) and BC (bottom panel) for the simulation period. IGP region is highlighted in orange colour.

emissions from GAINS emissions inventory for six pollutants ($PM_{2.5}$, BC, OC, SO_2, NH_3, NO_x and CO) were used as input in WRF-Chem simulations. The bottom-up GAINS emissions inventory consists of detailed anthropogenic emissions estimations from a total of ~30 sectors aggregated into six major emitting sectors (namely Agricultural burning, Energy, Industry, Transport, domestic, flaring and Waste). The annual emissions from GAINS were processed into monthly emissions using the monthly available activity patterns and sub-sectoral emissions from the GAINS emissions inventory. For the future scenario simulation, the initial and boundary meteorology inputs were kept the same as in 2018 to isolate the impact of only changes in anthropogenic emissions on air quality (Peng et al., 2020). A summary of model configuration and emissions input details for both scenarios is shown in Table 2. The spatial distribution of $PM_{2.5}$ and BC emissions averaged for November month for the baseline and alternative scenarios are shown in Figure 3. The IGP region shows the highest emissions and large reductions in 2030 under NZE-MFR enforcement. The contribution from the North-Western IGP region (namely the states of Punjab and Haryana) to the total emissions for both pollutants is highest in all of North India. However, by 2030, these regions' emissions will dramatically reduce due to stringent enforcement of bans on seasonal crop residue burning under the NZE-MFR scenario. Since BC emissions are mainly anthropogenic, by 2030, BC emissions are projected to show a more robust response to MFR controls. The annual emissions from the GAINS model are mapped onto the WRF-Chem domain by the anthropogenic emissions processor for the simulation period of 1-7th November. The results are presented in the following section.

Results and Discussions

Projected changes in emissions – GAINS Scenarios

The total emissions projection (kt/year) from Base-CLE, Base-MFR, SDS-MFR and NZE-MFR for the years 2018 – 2050 for India are presented in Figure 4. For $PM_{2.5}$, the projected total emissions in the Base-CLE scenario decrease sharply from 2018 to 2030 and then increase, albeit only marginally, in 2050 compared to 2030. The alternate scenarios with MFR technologies in place are expected to reduce emissions by far compared to the baseline emissions projections. Relative to the only marginal reduction of $PM_{2.5}$ emissions (~11%) from 2018 to 2050 under the Base-CLE scenario, BC emissions would reduce by over 50%. Whereas, BC emissions show over 90% reduction from 2018 to 2050 in NZE-MFR and SDS-MFR scenarios, and $PM_{2.5}$ emissions are expected to reduce by 85% compared to 2018. The model projects similar reductions for NZE-MFR and SDS-MFR scenarios for the years 2030 to 2050 for both pollutants.

Table 1. Summary of WRF-Chem Model configuration and emission data inputs for the two scenarios

Configuration and Inputs	**Method**
Horizontal resolution	12 x 12 km
Time period	2018 & 2030: November one week
Scenarios	1. Base 2. NZE MFR 2030
Boundary layer scheme	Yonsei University Scheme (YSU) scheme(Hong et al., 2006)
Gas-phase chemistry	Gas-phase chemistry MOZART-4 (chem_opt = 201)
Aerosol scheme	MOSAIC 4-bin (chem_opt = 201) (Zaveri et al., 2010)
Initial and boundary chemistry/ aerosol	MOZART-4 (Model for Ozone and Related chemical Tracers, version 4).
Initial and boundary and nudging meteorology	ECMWF ERA5 Reanalysis dataset 2018 at 0.25° x 0.25° spatial resolution
Anthropogenic Emissions	2018: For BC, NH_3, OC, SO_2, CO, NOx, $PM_{2.5}$ – GAINS 2018 emissions at 10 x10 km resolution For other pollutants: Emissions Database for Global Atmospheric Research (EDGAR- HTAP 2010) version 2.2 at 10 x10 km resolution 2030: GAINS projected emissions gridded to 10x10 km resolution based on 2018 monthly activity pattern, For other pollutants: same as 2018
Biogenic Emissions	MEGAN Model of Emissions of Gases and Aerosols from Nature at 1 km resolution

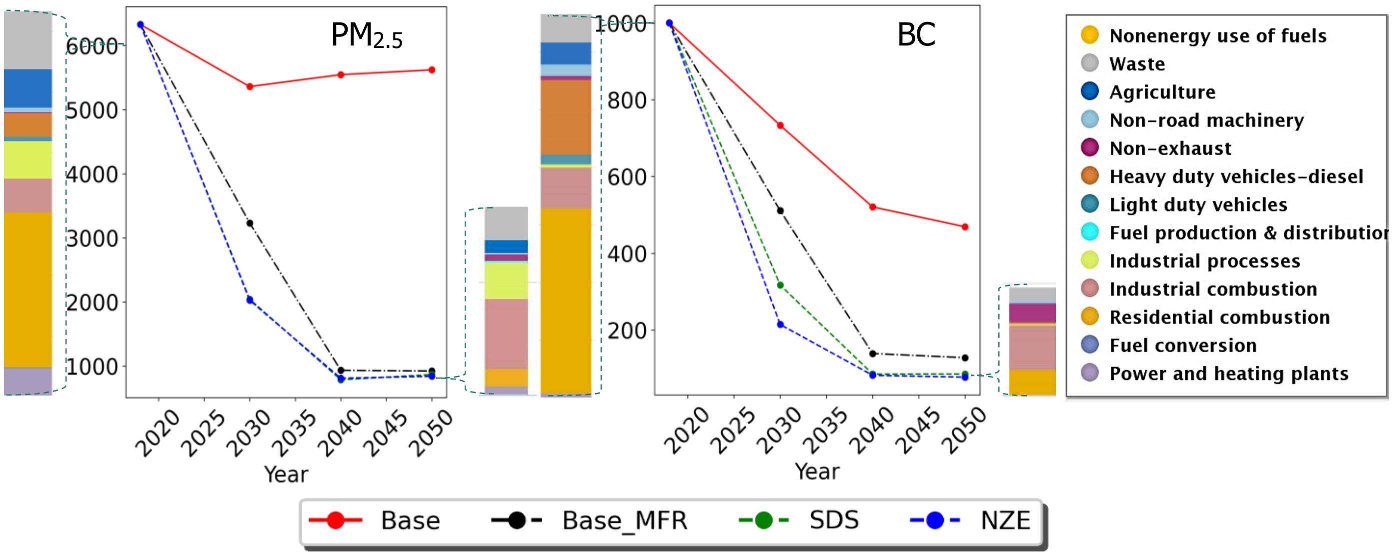

Figure 4. Projected $PM_{2.5}$ and BC Emissions from 2018 to 2050 from GAINS model. The bars show emissions contribution from each sector for $PM_{2.5}$ (left) and BC (right) for the year 2018 and 2050.

For $PM_{2.5}$ emissions, projected sectoral contributions in NZE and SDS scenarios show an increase in percentage contribution from industrial combustion (from ~10% in 2018 to over 40% in 2050) compared to the Baseline case. A similar case is observed for projected BC emissions for this sector. All three scenarios with MFR assume stringent emissions control technologies like the use of end-of-pipe emission controls, the use of clean fuel for cooking, electric cremation, updated transport emissions norms etc. (Amann et al., 2017; Majumdar et al., 2020). These results indicate the insufficiency of current legislation to improve the air quality in India and, consequently the need for stricter emissions control technology and policies. Earlier studies considering similar comparative emissions and policy scenarios found the SDS scenario to improve the air quality by 2050 and also achieve the NAAQS[2] targets for many states in India (Purohit et al., 2019). However, the modelled $PM_{2.5}$ concentration from GAINS for the year 2050 under the SDS scenario as calculated in Purohit et al. (2019) do not meet the latest clean air quality guidelines by WHO (5 $\mu g/m^3$ in 2021) for large parts of India. In the NZE and SDS scenarios, the contribution from the transport sector to total BC emission is expected to decline, while non-exhaust emissions are expected to dominate by 2050 relative to 2018. The residential sector is projected to contribute dominantly toward $PM_{2.5}$ and BC emissions by 2050. While for BC, emissions heavy-duty vehicles, which contribute primarily towards emissions in 2018, will completely phase out by 2050 in all MFR scenarios.

[2] National Ambient Air Quality Standard (NAAQS) by Central Pollution Control board of India for mean annual $PM_{2.5}$ concentrations of 40$\mu g/m^3$

Impact on Air Quality – WRF-Chem simulations

Model Evaluation

As the first step, the simulated $PM_{2.5}$ concentrations for 2018 are evaluated against the observed data from 76 monitoring stations in 40 cities across the modelling domain (Figure 5, left panel). The data was accessed from the OpenAQ platform (Open AQ, 2022), which sources data from Central Pollution Control Board (CPCB) and the US Embassy in India. The ground observations data were filtered based on data quality control approaches adopted in prior studies (Mogno et al., 2021; Schnell et al., 2018). The steps include 1. Filtering data for negative and zero values, 2. Filtering days where the number of hourly measurements was less than 12 hours, 3. Filtering stations with less than 20 days of measurements in the month. This results in a total of 76 independent stations for comparison of monthly mean $PM_{2.5}$ concentrations for November, shown in a spatial map in Figure 5. The scatter plot for paired modelled versus measured monthly averaged concentrations for $PM_{2.5}$ is shown in Figure 5.

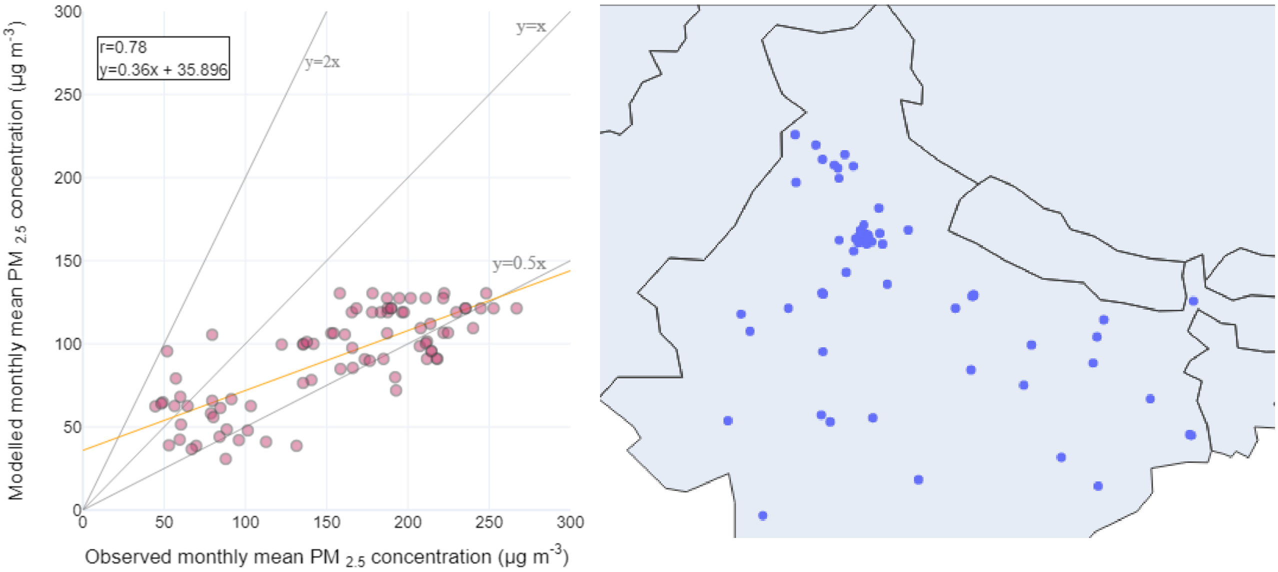

Figure 5. Model performance evaluation by comparison of simulated monthly mean $PM_{2.5}$ concentrations with ground monitoring data using scatter plot (left). The 1:1 line is represented by y=x in the graph. The values in inset on upper left show r value, slope, and intercept of the best-fit line. The spatial coverage of all the monitoring stations used for evaluation in this study is shown in the map on right.

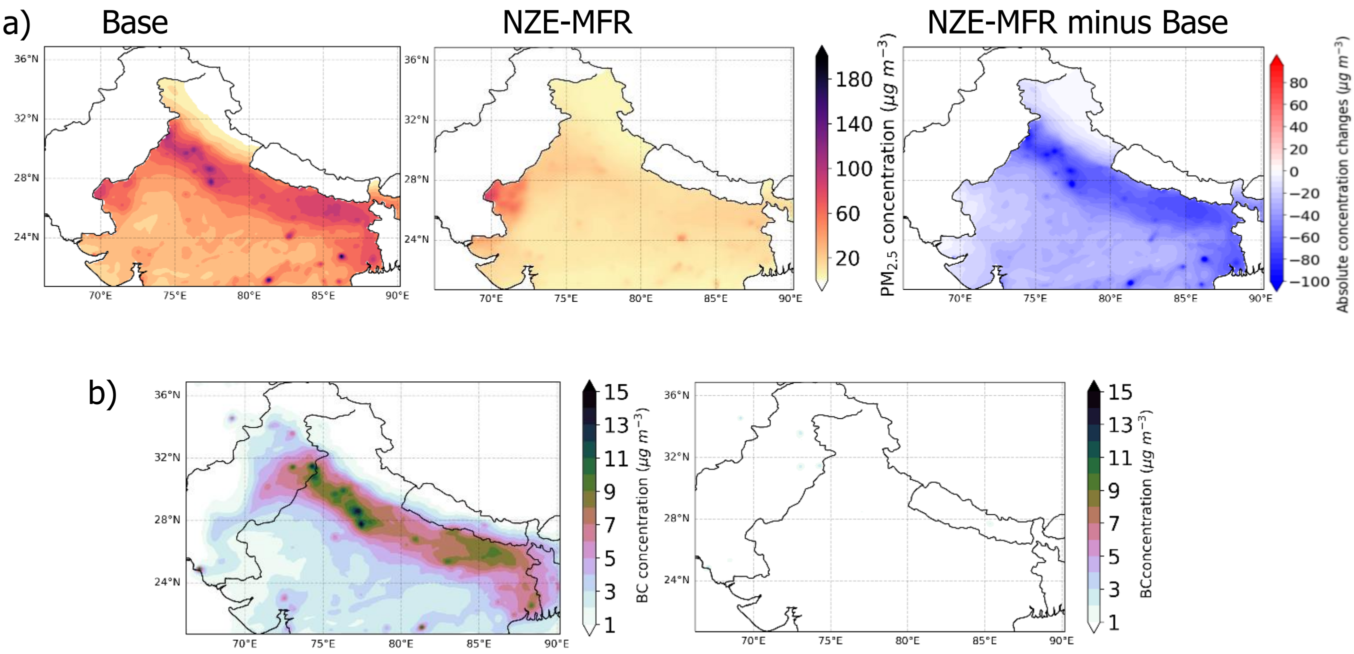

Figure 6. a) Spatial distribution of mean $PM_{2.5}$ concentrations (one-week) in 2018 and 2030 years and the absolute difference between the two scenarios (far left panel) b) Spatial distribution of mean BC concentrations, similar to $PM_{2.5}$ scenarios in 6a.

The model underestimates the $PM_{2.5}$ concentrations by a factor of 2 at high concentrations. The overall agreement between modelled values and ground measurements is reasonable (r=0.78) and falls within the correlation estimates found in the prior studies (Kumar et al., 2012; Mogno et al., 2021; Roozitalab et al., 2020). The model performs poorly in capturing the high mean values and, at some locations, tends to overestimate lower values. The overestimation in dilution and mixing in the boundary layer parametrisation potentially underestimated the pollutant concentrations near the ground surface in the model (Conibear et al., 2018; Kumar et al., 2012). Another reason for the bias in model estimates potentially arises from multiple sources of error, such as uncertainties due to unique topography in Northern India and systematic biases in reproducing the right meteorology in that region (Kumar et al., 2012). Additionally, most of the observation sites are located near the roadside or near dense urban settings, contributing to the model's skill in reproducing observed high $PM_{2.5}$ values.

Present and future $PM_{2.5}$ and BC concentrations

The air quality changes for Base and NZE-MFR 2030 scenarios are compared for one week in November. The modelled mean $PM_{2.5}$ concentrations with the policy and technology enforcements in place NZE-MFR scenario show a considerable reduction in both BC and $PM_{2.5}$ concentrations throughout the modelling domain (Figure 6). The largest reductions in $PM_{2.5}$ concentrations are observed in the IGP region. The $PM_{2.5}$ concentrations here decline by over 80%, as shown in the plot of the difference in Figure 6a. There is an evident regional spatial character in $PM_{2.5}$ concentration changes, which shows the highest reductions in hot spots of pollution in the central and central-eastern regions. Since BC emissions are reduced more dramatically in all the alternate scenarios, a more considerable contribution to the dip in $PM_{2.5}$ concentrations can be expected to come from the BC particles. The results indicate significant improvements in air quality with MFR controls in place.

We looked at select individual grid boxes in the Northern Indian region (corresponding to in situ measurement sites) and observed reductions within the range of 30 – 98 μgm^{-3} compared to base (Figure 7a). In terms of percentage reductions over the in situ sites, the IGP stations show more considerable improvements overall. Venkataraman et al., 2018 also find similar spatial regional heterogeneity in $PM_{2.5}$ drops in an ambitious policy scenario in 2030 and 2050. The dominant contribution to total $PM_{2.5}$ emissions is projected to come from

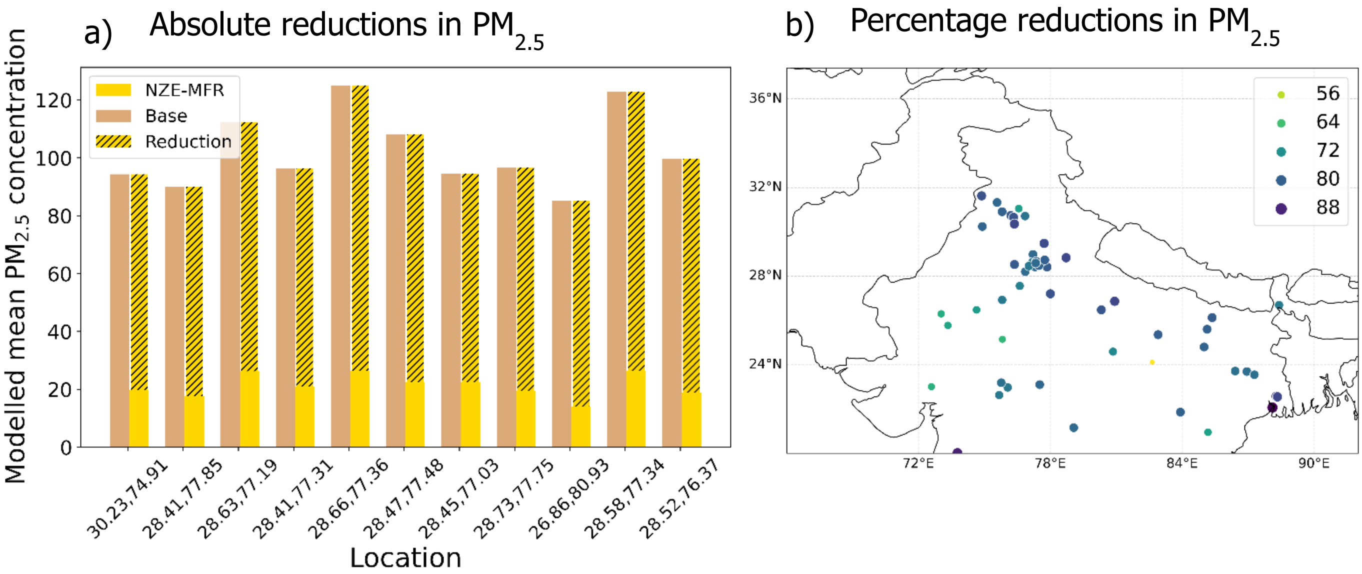

Figure 7. a) Sensitivity to simulated $PM_{2.5}$ concentrations to change in precursor emissions over selected locations in the study region. The bars show comparison between base and NZE-MFR cases and the reductions due NZE-MFR enforcements are shown as shaded regions of the bars. b) Spatial map showing percentage reductions in $PM_{2.5}$ concentrations over the ground monitoring locations. The size of circle corresponds to magnitude of percentage reductions.

industrial processing alternate scenarios by 2030 and 2050. This means clean residential fuels will significantly improve India's air quality, but focusing on this sector solely does not meet the WHO 2021 air quality targets. Even with the combination of the most advanced control technologies and policy interventions in the NZE-MFR scenario, the mean $PM_{2.5}$ concentrations exceed by about 2 times WHO 2021 guidelines in most locations.

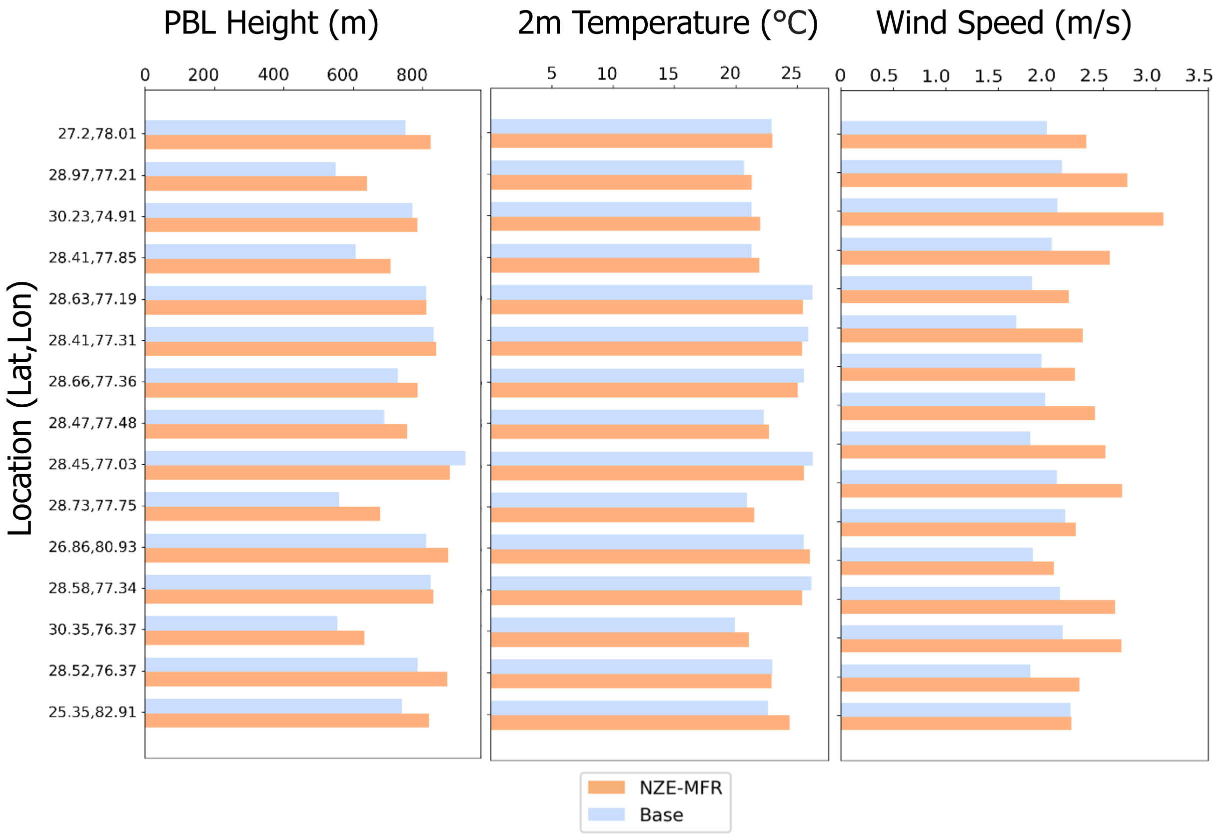

Figure 8. Projected sensitivities to meteorology drivers for 2018 and future case scenario

These estimates suggest uncertainties and limitations of the model and the future air quality predictions for the Indian region. Since the experiments here isolate the changes in anthropogenic emissions only, the contribution from future evolution of dust and biogenic emissions remains unaccounted for in these estimates. Prior studies have found natural dust to contribute to $PM_{2.5}$ concentrations in India (Kumar et al., 2014; Roozitalab et al., 2020). The likely evolution of natural sources of $PM_{2.5}$ under climate change is one of this study's main limitations, which needs to be addressed in future work.

Impact on meteorological drivers

Given the frequent occurrences of high pollution events over Norther India in the autumn season, there is also a need for understanding the dynamics during the event, which aggravates short-term exposure to air pollution by many folds. WRF-chem offers a potential advantage for this exploration as it couples the meteorology with the chemistry parametrisations and outputs the chemistry component. This means it is possible to quantify the changes in meteorology due to changes and future evolution of emissions patterns. As a preliminary investigation, this study looks at the model's meteorological parameters that control the evolution of near-surface pollutant concentrations. It is crucial to note here that the future development of climate and weather is likely to impact the results observed here, which use fixed meteorology of 2018 and is, therefore, biased toward meteorological conditions not necessarily representative of the change in climate in the future. Despite this, the current results provide us with the best understanding of the dynamics in the ambient atmosphere and isolate the impact of anthropogenic activities on future air quality. As shown in figure 8. under the improved air quality future case in 2030, the Planetary boundary layer height (PBLH/PBL) increases over the locations in North India. This is particularly crucial for the mixing and dispersion of pollutants near the ground. The 2m temperature values and wind speed also show sensitivity to future air quality changes. The top of PBL height allows for enhanced mixing, while wind speed controls the strength of the mixing, which is increased in the future scenario. The sensitivity, however, is not linear for all the locations and suggests the dynamics in the atmosphere to be more closely interlinked. Therefore, the sensitivity of meteorological parameters indicates a more holistic approach when estimating the evolution of future air quality by considering the non-linear chemical environment in the model and ambient atmosphere.

Conclusions

This study assesses the effectiveness of future mitigation policies and the impact of anthropogenic emissions changes on air quality. At present, the current emissions control measures aren’t stringent enough to improve the air quality over Northern India. Ambitious control measures targeting multiple pollutants would efficiently mitigate co-emitted climate-relevant species like BC. Even with the successful implementation of most advanced control measures combined with stringent policy enforcements, the future $PM_{2.5}$ concentrations do not meet the latest WHO 2021 AQG for pan India. BC emissions reductions are expected to contribute dominantly towards the expected improvements in the air quality, with residential emissions to decline completely by 2050 with clean cooking policies (i.e. net zero emissions scenario). However, it is still possible under the most ambitious control policies to meet most of India's annual and 24-hour interim targets of 15 µg/m^3 (WHO,2021). In addition to meeting annual $PM_{2.5}$ targets, there is a need to account for the evolution of meteorological influences on ambient air quality and the likelihood of future haze episodes. Sensitivity to meteorological parameters illustrates that reducing primary pollutants emissions, e.g. BC, also reduces conditions detrimental to haze pollution development.

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