Air Pollution and Health in Delhi, India: Health Effects of Short-Term Exposures and Policy Implications

This Doctoral Project, *Air Pollution and Health in Delhi, India: Health Effects of Short-Term Exposures and Policy Implications*, presented by *Bhargav Krishna*, and Submitted to the Faculty of The Harvard T.H. Chan School of Public Health in Partial Fulfilment of the Requirements for the Degree of *Doctor of Public Health*, has been read and approved by:

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Date: April 7, 2021

AIR POLLUTION AND HEALTH IN DELHI, INDIA:
HEALTH EFFECTS OF SHORT-TERM EXPOSURES AND POLICY IMPLICATIONS

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A Dissertation Submitted to the Faculty of

The Harvard T.H. Chan School of Public Health

in Partial Fulfilment of the Requirements

for the Degree of *Doctor of Public Health*

Harvard University

Boston, Massachusetts.

May 2021

Thesis Advisor: Prof. Joel. D. Schwartz Bhargav Krishna

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Abstract

Air pollution exposure is recognized as an important contributor to premature mortality and morbidity globally. Exposure to ambient particulate matter smaller than 2.5 microns in aerodynamic diameter ($PM_{2.5}$) has been associated with all-cause and non-accidental mortality, cardiovascular and respiratory diseases, premature births and birth defects, and neurocognitive deficits, among other conditions. India is home to some of the most polluted cities on the planet, the chief among them being Delhi. Ambient air pollution ($PM_{2.5}$) levels in Delhi routinely exceed World Health Organization (WHO) guidelines and Indian National Ambient Air Quality Standards (NAAQS) for safe levels of daily exposure, contributing to a large and preventable burden of diseases. While air quality has worsened in Delhi over the last two decades, action to reduce emissions from polluting sources has been scarce at best. This lack of action has been teamed with pushback against most epidemiological evidence published in the last few years showcasing the harmful effects of air pollution in Delhi and in India.

To address the dual gaps in locally generated evidence, and level of trust in this evidence among various key stakeholders, this project aimed to:

- Generate local evidence on the short-term impacts of $PM_{2.5}$ exposures on non-accidental mortality

- Translate that evidence for a diverse set of stakeholders including policymakers, the media, and the general public

Utilising mortality data obtained from the municipal government of Delhi for the period June 2010-December 2016, I conducted epidemiological analyses to understand these associations. I found that each 25 μg/m^3 increment in daily $PM_{2.5}$ exposure was associated with a 0.8% (95% CI: 0.3, 1.3%) increase in daily non-accidental mortality in the study population and a 1.5% (95% CI: 0.8, 2.2%) increase in mortality among those aged 60 or over. The exposure-response relationship was non-linear in nature, with relative risk rising rapidly before tapering off above 125 μg/m^3. Meeting WHO guidelines for safe levels of exposure over the study period would have averted 17,526 (95% CI: 6837, 25589) premature deaths, with older and male populations disproportionately affected.

The findings of this study are highly relevant for policy as Delhi and India move forward to reform environmental regulations governing air quality. Over the course of the project, I have also formulated a translation and dissemination strategy that will aid in simplifying the complex epidemiological findings of this study for key stakeholders, in addition to building trust in the process of evidence generation among decision-makers. By engaging through the entire paradigm of research to policy, I hope to better inform otherwise antagonistic or agnostic policymakers, raise awareness among those most affected by air pollution exposure in Delhi, and aid citizens to more effectively advocate for their right to clean air in one of the most polluted cities on the planet.

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Acknowledgements

This thesis is dedicated to my grandfather Parthasarathi Rajagopalachari who instilled in me an intellectual curiosity, a dedication to a higher cause, and the strength to persevere through the most challenging times.

I am deeply grateful to my advisor Prof. Joel D. Schwartz for his mentorship and guidance as I navigated the world of environmental epidemiology. I would also like to thank my committee members, Dr. Gary Adamkiewicz and Prof. K. Srinath Reddy for sharing with me their guidance, expertise, and feedback as this project developed. I am thankful to Prof. D. Prabhakaran and colleagues at my host organization the Centre for Chronic Disease Control for their support in developing this work, and to the GEOHealth India Hub funded by the Fogarty International Centre for its financial support.

I have also been lucky to have the company of my passionate, intelligent, and generous colleagues Joseph Corlis, Cristina Alonso, and Emily LaRose in the DrPH program, who have challenged me to grow at every turn. I am grateful to Dr. Richard Cash for his endless wisdom and considerate guidance. Thank you also to Dr. Nancy Long-Sieber, Dr. Anne Litwin, Gary Williams, and others who have fielded my numerous concerns, queries, and challenges with patience and kindness.

My family, especially my parents Priya and Krishna, have been an constant source of encouragement and confidence. Finally, none of this would have been possible without the endless love of my wife Sagri, whose compassion, generosity and emotional strength carried me through these three challenging years.

Air Pollution and Health in Delhi, India:
Health effects of short-term exposures and policy implications

1. INTRODUCTION

Global evidence indicates that ambient air pollution is a major public health hazard, with harmful associations being reported with respect to all-cause mortality (Di et al., 2017; Samet et al., 2000; Zanobetti & Schwartz, 2009), cause-specific mortality from cardiovascular (Dehbi et al., 2017; Yap et al., 2019) and respiratory diseases (Mokoena et al., 2019; Xue et al., 2018).

Air pollution exposure is a major and growing risk factor for ill health and premature death in India, with the 2017 sub-national burden of disease estimates for India stating that over 670,000 premature deaths annually are attributable to ambient PM2.5 exposures (particles smaller than 2.5 microns in size). With a rapidly growing transport fleet, vast availability and usage of highly polluting coal, and increasing migration to major urban centres, India is home to 21 of the 30 most polluted cities globally (World Health Organization, 2014). Additionally, the wide prevalence and continued use of solid fuels for cooking and heating in many parts of rural and peri-urban India, contributes not only to high levels of household air pollution exposure, but also to the ambient air pollution loading (Balakrishnan et al., 2019; Krishna et al., 2017).

While large parts of India currently experience air pollution (specifically PM2.5) beyond levels considered safe for daily and annual exposure by the WHO (10 and 25 μg/m^3 respectively), Delhi has received particular media and policy attention over the years (World Health Organization, 2014) given its special status as the capital of the nation. A variety of point (e.g., power plants, industry), line (e.g., traffic emissions), and diffused sources (e.g., construction dust, trash burning) contribute to a large and mixed particulate matter load in the city, differing often by season.

This mixed load also ensures that action to curb any one source alone is insignificant in reducing overall exposures. As a result, annual average exposures to PM2.5 in Delhi exceeded 130 μg/m^3 in 2016, having grown steadily over the previous 7 years, with large spatial and temporal variations (Mandal et al., 2020). Seasonal factors, high emissions related to fireworks combustion during religious events and periodic crop-stubble burning also contribute to extremes of PM2.5 in the winter which can sometimes breach 1000 μg/m^3 (McCall, 2019).

Over the years, a growing and significant body of work has documented the health effects of exposure to PM2.5 both in household and ambient settings, with a focus more on chronic longer-term exposures (Balakrishnan, Krishna, et al., 2015). High levels of PM exposures in the short (Cropper et al., 1997; Maji et al., 2017; Rajarathnam et al., 2011) and long-term have been shown to have health effects in India as well, with PM exposure a key risk factor for the burden of disease in the country (Balakrishnan et al., 2019; Krishna et al., 2017).

However, there is limited evidence on the short-term effects of PM2.5 on mortality and morbidity in India, with only one time-series study conducted till date anywhere in the country documenting the effect on daily mortality (Gordon et al., 2018; Singh et al., 2019). This lack of evidence of the short-term impact, and more importantly the impact on mortality, is cited regularly by policymakers as a reason for inaction. While air pollution impacts human health in very similar ways across different parts of the world, the need for local evidence that is grounded in measured and not modelled data remains salient, especially in alleviating concerns (legitimate or otherwise) of those in policymaking circles.

Policy change on air pollution has also been stymied as a result of push-back from policymakers for a variety of reasons, and has not been helped by poorly designed studies, the results of which have often been miscommunicated to the public by the media. Driving effective policy change on air pollution will require a considered approach that fills in the knowledge gaps in epidemiological evidence and buttresses that with an effective framework for translation and communication to all relevant stakeholders.

Through this project I aimed to do both of those things by first studying the effect of short-term exposures to PM2.5 on daily mortality in Delhi. I then aimed to translate and communicate the findings of my work directly with relevant stakeholders through appropriate fora and means sequentially. This work has direct implications on the policy direction that environmental regulators need to take moving forward, and to that end, effective communication can ensure that the right messages get through.

Therefore, this project aimed to address two primary issues:

- Generating local evidence on the short-term impacts of PM2.5 exposure on mortality
- Translating that evidence for a diverse set of stakeholders including policymakers, the media, and the general public

2. BACKGROUND

Air pollution levels in Delhi routinely exceed World Health Organization guidelines and the Indian National Ambient Air Quality Standards for safe levels of daily exposure, particularly to $PM_{2.5}$. A number of studies have been published over the last few years, and several are currently underway, documenting the burden of disease attributable to $PM_{2.5}$ exposures in India, focusing primarily on chronic long-term exposures and outcomes including cardiovascular and respiratory diseases (Arku et al., 2020; Balakrishnan, Sambandam, et al., 2015). Only two have examined the short-term effects of exposure to high levels of ambient air quality on daily mortality in Delhi, and they were conducted in the late 90s and in 2010 respectively, with the primary exposure of interest being coarse particulate matter under 10 microns in size or PM_{10} (Cropper et al., 1997; Rajarathnam et al., 2011).

2.1 Historical context and policy relevance

By the turn of the millennium, Delhi had earned a reputation as a highly polluted city, with a variety of local sources including brick kilns, stone crushing units, and old diesel vehicles contributing to a critical ambient air pollution load. Having noted this problem, concerned citizens, among them a local lawyer named MC Mehta filed public interest litigations in the Supreme Court of India, calling for urgent action. With guidance from environmental experts, the Court directed the Central and State Governments to take urgent action on the issue by expediting the purchase of new compressed natural gas (CNG) buses to replace the highly polluting diesel bus fleet of the time (Dayal, 2016; R. Mehta, n.d.; Supreme Court of India, 2001). This transition, while taking several years to implement, was one of the first direct policy actions led by the Court in the face of both Governments' reluctance to really drive reductions in pollution, fearing the perceived harm to industrial and economic growth (Narain & Krupnick, 2007).

In subsequent years, the Supreme Court took on more of an 'Executive Court' avatar, first appointing an *Amicus Curiae* to guide decision-making on new policy, and then establishing the Environment Pollution (Prevention & Control) Authority for the National Capital Region (EPCA) to help implement said policies due to a lack of cohesive and collaborative action across different line ministries (Bhatia, 2019). With authority under the Air (Prevention and Control of Pollution) Act (1981), EPCA, under the leadership of a former senior bureaucrat and with members including environmental scientists and advocates, was given sweeping authority to direct the local governments to take appropriate action. EPCA's actions over the next 20 years contributed to several important milestones, including the banning of polluting fuels such as pet coke from industrial units, the relocation of polluting brick kilns, and the accelerated transition to cleaner standards for vehicular emissions. However, EPCA's actions were too small in scale for a city growing rapidly in terms of both geography and population (Dutta, 2018).

Delhi also hosted the Commonwealth Games in 2010, bringing into stark focus its deteriorating air quality. In the 20 years since the landmark CNG transition, Delhi's vehicular and human population more than doubled, with the National Capital Region now encompassing the capital Delhi, and the satellite cities of Gurgaon, Ghaziabad, Noida, and Faridabad, accounting for an urban agglomeration of more than 20 million people. This has negated any gains made in the interim, and air quality has continued to worsen over this time period, not least because of continuing government subsidies to polluting diesel vehicles (Beig et al., 2013). Other minor remedial actions during this period also had little impact (Narain & Krupnick, 2007).

The publication in 2013 of the Institute for Health Metrics and Evaluation's "Burden of diseases report", that documented the major causes of death and disability in 2010 and their contributory risk factors, shone the international spotlight on Delhi and India's air pollution problem. Noting that over 1.5 million deaths in 2010 were due to ambient and household air pollution, the report made headlines not only in national dailies, but the international press started reporting on the state of air quality in India as well (Harris, 2014; Lim et al., 2012) . The release of the WHO's "list of the most polluted cities around the world" that followed, had Delhi topping the list. This led to sustained media coverage in the subsequent months, prompting public outcry and calls for action by the Government.

In recognition of this pernicious health threat, the Ministry of Health of the Government of India convened an expert group in early 2014 to study the health effects of air pollution and report on actions that could be taken to alleviate the associated burden of disease (Balakrishnan, Krishna, et al., 2015). The report's key recommendations focused on household air pollution exposures, and actions based on those recommendations led to the roll-out of the *Pradhan Mantri Ujjwala Yojana* which expanded access to cleaner cooking gas to millions of homes in rural India (Tripathi & Sagar, 2019). However, recommendations on ambient air pollution, including tighter emissions standards for industrial sources, and a more rapid transition nationally to stringent vehicular standards did not find much purchase in policy circles.

The filing of further PILs at the Supreme Court with pleas for action on annual Diwali fireworks related pollution and pollution due to crop stubble burning in winter led to the Court directing EPCA and the local State Governments to establish emergency measures to deal with these seasonal highs. With winter levels often touching 1000 ug/m3 due to a combination of geography, meteorology, and seasonal sources, pollution during this period was viewed as the most urgent to address. As a result, the Graded Response Action Plan came into being in 2018. The plan outlined specific actions to be taken based on the air quality index including shutting down all construction activities, closure of thermal power plants, and road rationing, among others. The Supreme Court's directions also led to a ban on the sale of fireworks in the National Capital Region, although this direction was less stringent in its implementation (Sikri, 2018).

GRAP and its associated actions have had mixed success in reducing air pollution, and more importantly, in bringing them to levels considered safe by both the NAAQS and the WHO guidelines (Dubash et al., 2018; Dubash & Guttikunda, 2018). If anything, these actions have served to simply reduce exposures from extraordinarily high (15-20 x WHO guidelines) to severely high (5-10 x WHO guidelines), which as we know from existing exposure-response relationships, has little overall incremental benefit for health. The lack of evidence on the short-term impacts on mortality and morbidity have also created a vacuum, as a result of which any minor reduction in ambient loads is trumpeted as a success.

2.2 The need for local evidence

Till date, no studies have been conducted to examine the association between short-term exposures to PM2.5 and daily mortality in Delhi. Most policy interventions in Delhi, including those under the graded response action plan, focus on reducing the high exposure levels in winter months, with little evidence to show thus far that they have had any effect at all in improving air quality (Chowdhury et al., 2017; EPCA, 2018; Kumar et al., 2017). Additionally, long-term goals for reductions in air pollution set under the National Clean Air Program have targeted a 30% reduction from 2017 levels in ambient air pollution, which, given the current evidence already available, and the new evidence we have generated from this study, would prove inadequate to sufficiently protect human health.

To ensure that policies are aligned with the evidence by pursuing initiatives that produce appropriate reductions in $PM_{2.5}$, there is a need to understand the dose-response relationship in local conditions , the preponderance of smaller sources of emissions, and baseline high level of exposure coupled with extreme seasonal exposures (Gordon et al., 2018). This was also a lacuna in the evidence as identified both by the "Report on air pollution" of the Ministry of Health and Family Welfare Steering Committee published in 2016 by the Government of India (Balakrishnan, Krishna, et al., 2015), and by an expert group of Indian and American scientists in the field specifically convened for a workshop to identify research priorities for air pollution and health research in India (Gordon et al., 2018).

In addition to the above-mentioned aspects, another innovation in this study will be the first direct quantification of the burden of mortality attributable to air pollution exposures. Ratio measures are traditionally used to communicate effect summaries in epidemiological studies, and while they are useful to summarize the health impact of the exposure, they generally provide less useful information for the planning and implementation of public health programs.

In contrast, the attributable fraction, or fraction of cases or deaths attributable to the exposure of interest, and the attributable number, or absolute number of cases or deaths attributable to the exposure of interest, provide such information, which is of greater relevance and utility to policymakers. They also have greater relevance in communication of this information to the broader public since there is a "body count" associated with the analyses (Steenland & Armstrong, 2006). In a political scenario such as in India, where there is a high-level of push back against modelled epidemiological studies (such as the Global Burden of Diseases study (Balakrishnan et al., 2019)), a combination of data based on recorded mortality numbers coupled with local exposure data, presented in the form of attributable fractions and numbers would generate far greater interest among policymakers (Gordon et al., 2018).

2.3 Framework for change

This project presents an opportunity to conduct science within a somewhat contested space in India. While there is a large body of global evidence on the health impacts of air pollution, India still has several gaps in evidence that need to be addressed, including the effect of short and long-term exposures of PM2.5. The latter need is being addressed through the conduct of several cohort studies that are examining the impact of household and ambient PM2.5 on chronic diseases. The evidence base for the former is scant with little new work planned. The reasons include poor quality and lack of availability in the public domain of both PM2.5 and civil registration data (births and deaths). This results in a paradoxical situation where the only form of evidence that is being generated is from modelled studies such as the Global Burden of Diseases study. Modelled evidence is based on several assumptions, and the lack of contextual data that could feed into these models for India drives pushback from policymakers on the validity of such evidence. While it could be argued by researchers that air pollution affects health no differently in different parts of the world, the generation of contextual evidence can add not only scientific but also public narrative value.

We can therefore examine air pollution exposures in Delhi, and in India more broadly, as not just a technical but also an adaptive challenge (Heifetz & Linsky, 2002). The technical aspects of the challenge include the fact that the sources and the solutions are already known and well-documented not just locally but globally. The adaptive component here involves framing the public narrative in a manner as to drive change that has so far been challenging to bring about. Over the last few years, as greater evidence has been generated from modelled studies, showing the harmful effects of the high levels of air pollution exposure in India, there has been significant push-back from the political class and bureaucracy (PTI, 2019; Safi, 2017). While some of this push-back has been reflexive in its defensiveness, the hypothesis for our second aim is to understand whether an underlying lack of understanding of epidemiological processes and how they generate evidence also play a part in this (Krishna & Reddy, 2018). Specifically, in a domain dominated by environmental engineers who have little understanding of both biological processes and epidemiological research methods, there is a greater onus on epidemiologists and public health professionals to engage at multiple stages of a study from initial conception through to final publishing. Politically, this could also alleviate concerns that may be present in the minds of those relevant officials whose job it is to respond to media queries when studies are published that show significant impacts.

To carry out this work, I utilized the FHI360 research utilization framework described in figure 2 below (Kim et al., 2018) as the theoretical underpinning. A distillation of key concepts from other existing frameworks for knowledge translation, the FHI360 framework provides a basis to understand the various aspects of work required, from generation of foundational understanding of issues to institutionalization of core policies. Through the various stages, the authors of this framework identify two core decision points related to methods to translate and to adopt relevant knowledge. The vast majority of work done by academics traditionally restricts itself to phases 1 and 2, which involve understanding the knowledge gaps and conducting research to plug those gaps. While this project aimed to also address phases 1 and 2 through the generation of new knowledge, deeper engagement with this framework to achieve broader goals meant going beyond that. Translation of research is frequently left by academics to other actors in the system, traditionally "knowledge brokers" within this framework, including the media and advocacy organizations. However, there are significant challenges in ensuring effective translation and subsequent adoption of knowledge, if the communication of the research findings is done by actors who may not have a good understanding of the underlying disciplinary principles and uncertainties, or of the rationale and direct policy implications of those findings.

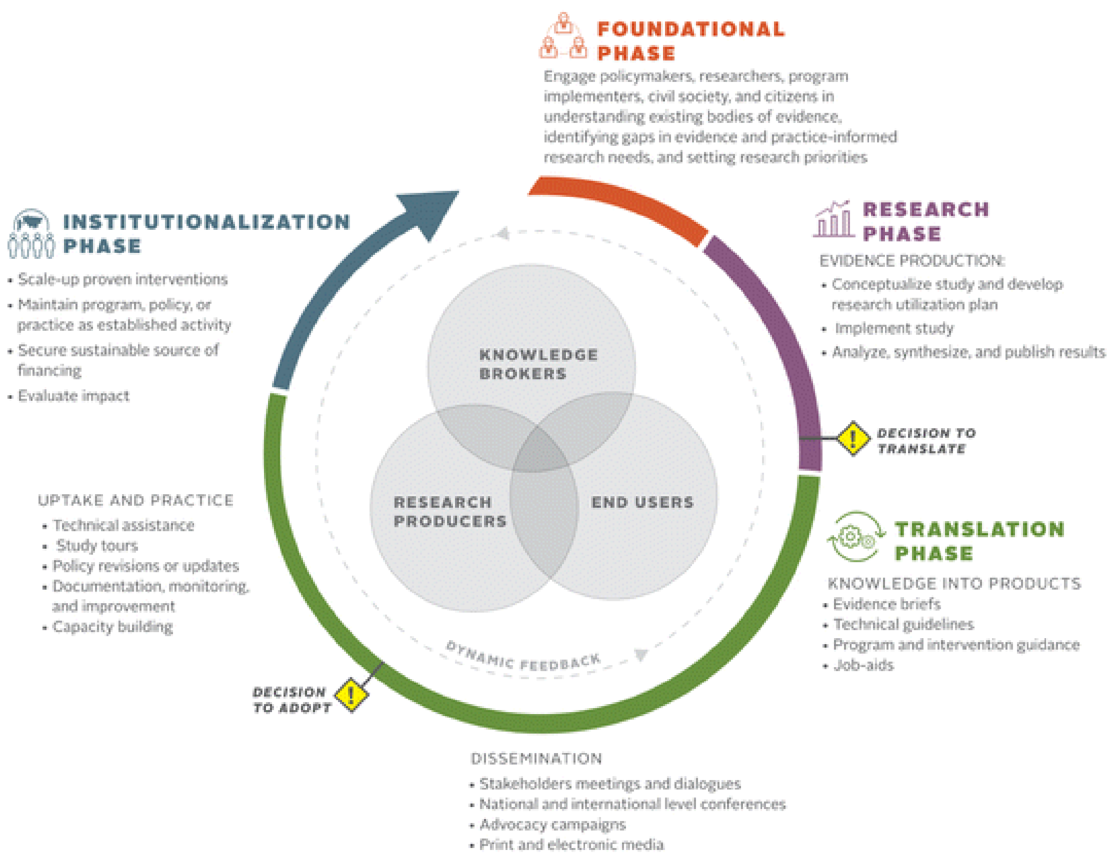

Figure 1: FHI360 knowledge translation framework

To try and address this, I aimed to address the challenges involved with both the research and translation phase through several steps:

1. Conduct the primary epidemiological study to fill the identified gaps in knowledge
2. Publish these results in an appropriate academic journal
3. Engage with policymakers from the outset, explaining clearly at each step the assumptions underlying the analyses, and possible outcomes
4. Generate communication products by distilling complex epidemiological findings into relevant information packets for specific audiences including policymakers, advocacy organizations, and the general public, through issue briefs
5. Disseminate findings through multiple fora sequentially to ensure appropriate dissemination of the findings and implications of this work to all relevant stakeholders

The above-mentioned approach, encompassing aims 1 and 2 of the project, attempts to bring a holistic view to the work carried out. Much of the approach was outlined before the onset of the Covid pandemic and its consequential global and local effects. Given the impact of Covid, not all of these steps were achieved within the timeframe of the project, and goals were re-oriented with approval of my committee. These challenges and subsequent changes are discussed in later sections.

3. DATA AND METHODS

The concurrent nature of the research and translation aspects of this project present an opportunity to conduct the work of the "research producer" in a way that has not been done before. Not usually considered a part of the academic's remit, the translation and communications aspect of this project will aim to facilitate a broader engagement and foster trust for an issue that continues to prove challenging in public discourse in India. To this end, this section outlines the various methods that are employed in the research and translation aspects of this project.

3.1 Environmental Data:

Monitored $PM_{2.5}$ data were not widely available for large periods, especially in the early part of our study period (2010-2016), with spatial and temporal resolution of monitored $PM_{2.5}$ increasing gradually towards the end of said period. To ensure adequate temporal coverage of $PM_{2.5}$ data, we utilised predicted $PM_{2.5}$ from a model developed by members of this study group as part of the India GEOHealth Hub (Walia et al., 2020). The model described in detail by our colleagues (Mandal et al., 2020) utilises an ensemble averaging approach to predict $PM_{2.5}$ at high temporal and spatial resolution (daily at 1x1 km grids over Delhi). In a multi-stage approach, the model utilised satellite-derived AOD, ground-monitored $PM_{2.5}$, land-use variables, meteorological variables, and chemical transport models to predict 24-hr average $PM_{2.5}$ exposures at 1x1 km grids across Delhi with a cross-validated prediction accuracy of 80% over the study period.

From this model, we took the gridded 24-hr $PM_{2.5}$ predictions and averaged them at a city level to derive a single daily $PM_{2.5}$ exposure metric. Daily lagged exposure metrics were generated as well. Meteorological variables such as temperature and relative humidity were obtained from global climate re-analysis data of the European Centre for Medium-Range Weather Forecasts (ECMWF), which are downscaled from 25x25 km grids. Daily lagged variables were generated for temperature as in the case of $PM_{2.5}$.

3.2 Mortality Data:

To conduct our analyses, we used daily mortality data from Delhi. Death records for the period between June 2010 and December 2019 were obtained from the New Delhi Municipal Council, and the Municipal Corporations of East, North and South Delhi which, taken together, comprise between 97-99% of all recorded deaths in the city every year. Data for the Delhi Cantonment Board, which accounts for the remaining deaths, and which falls under the purview of the Indian Army, was not available. The administrative boundaries of the various corporations are shown in figure 2 below.

Figure 2: Municipal Corporations of Delhi boundaries and assembly constituencies

We obtained de-identified mortality records for the period 2010-2016 from the Municipal Corporation of Delhi (North, South, and East) and the New Delhi Municipal Council. These data were provided to us in their raw form and it took several months to clean and aggregate the data due to issues with coding of deaths, availability of information on sex and age, and identifiers for location. Additionally, given Delhi's prominence as the national capital, home to some of the best medical facilities nationally, and given that people come to Delhi from outside the NCR for treatment, we also had to do significant cleaning of the data through local language processing to exclude those who died in Delhi but were from other neighbouring States or from elsewhere in the country. This took significant time and learning. On completion of the cleaning process, all data were aggregated to generate daily counts of deaths overall and for various strata for the stated time period. While the availability of data on age for all, and sex for three of the four municipal corporations (not available for NDMC) enabled us to conduct further stratified analyses, discrepancies in coding the cause of death prevented us from conducting analyses of cause-specific mortality. This issue of cause of death coding was further challenging to explore, since, while the State publishes annual mortality statistics that include cause-of-death data, there is little clarity as to how these raw data are processed and interpreted to generate these annual statistics.

This study was restricted to the time period June 2010-December 2016, since exposure data has not yet been modelled for the period from January 2017-June 2019. Cumulative non-accidental deaths for this period are approximately 700,000 in number, with ~53% of deaths among men and ~34% of deaths registered at a healthcare institution. Table 1 below details the cumulative deaths by year for the period 2010-2016 used for preliminary analyses.

Table 1: Annual deaths across the study period

Year	Deaths
2010 (June-December)	53,726
2011	93,058
2012	97,491
2013	106,002
2014	109,399
2015	114,753
2016	126,083
Total	**700,512**

The Registry of births and deaths in the National Capital Territory of Delhi are maintained by the five municipal corporations, namely the North, South, and East Delhi Municipal Corporations (which fall under the Municipal Corporation of Delhi), the New Delhi Municipal Council (NDMC), and the Delhi Cantonment Board. We obtained de-identified mortality records for the period 2010-2016 from the Municipal Corporation of Delhi (North, South, and East) and the New Delhi Municipal Council. Deaths registered in these regions together accounted for 97-99% of all deaths that occurred in Delhi during the study period. Data were not available for the Delhi Cantonment Board area of the city since falls under the purview of the Indian Army. These data were then cleaned and aggregated to generate a count for daily deaths to be used in our analyses. While the availability of data on age for all, and sex for three of the four municipal corporations (not available for NDMC) enabled us to conduct further stratified analyses, discrepancies in coding the cause of death prevented us from conducting analyses of cause-specific mortality.

3.3 Statistical Analyses:

We studied the association between daily count of non-accidental deaths and daily $PM_{2.5}$ exposure. The analysis period covered six and a half years (June 2010 to December 2016). We examined the effect of temperature both as a variable in the model and as an effect modifier in the relationship between $PM_{2.5}$ and daily non-accidental mortality. We used generalized additive models (GAMs) in a time-series design to examine the association, and the relationship was modelled using quasi-Poisson regression to account for overdispersion.

In our GAM framework, we used a linear term for $PM_{2.5}$ to generate point estimates, and a penalized spline to explore non-linearity in the exposure-response relationship. We also examined the effect of different lagged exposures to $PM_{2.5}$ using the DLNM framework before choosing the lag-0 $PM_{2.5}$ average as our exposure of interest (Bhaskaran et al., 2013; Gasparrini & Leone, 2014).

Additionally, we also examined the effect of different lagged effects of temperature and included in our final model a penalized spline for 5-day average temperature prior to the day of the event. Also included in the model were a penalized spline for 5-day relative humidity and a natural spline for time in days with 1.5 degrees of freedom per season per year to account for long-term trends and year-specific seasonality. A dummy variable for day of the week was also included. The final model used was as follows:

$$\log(E[Y_i]) = \alpha + \beta_1 . PM_{2.5} + \beta_2 . s(Temp) + \beta_3 . s(RH) + \beta_4 . ns(Time_i, df = 49) + \beta_5 . DOW_i$$

where $E[Y_i]$ is the expected count of non-accidental deaths on day *i*; α is the intercept; β_{1-5} are regression coefficients; $PM_{2.5}$ is the 2-day average $PM_{2.5}$ exposure; *Temp* is 5-day average temperature exposure; *RH* is 5-day relative humidity; *Time* is time in days from June 1st 2010; *DOW* is day of the week; *s* is a penalized spline function, and *ns* is a natural spline.

We conducted sensitivity analyses using same-day temperature as a linear term with thin plate spline of temperature and $PM_{2.5}$, or as a categorical term (Cold (<15℃); Normal (15-

31℃) and Hot (>=32℃)) in interaction with the exposure of interest. We also examined effect modification by season, sex, and different age strata through the introduction of an interaction term with the primary exposure. We excluded outliers of exposure (1^{st} and 99^{th} percentiles) in our analyses. All statistical analyses were conducted using R statistical software version 4.0.1 (R Foundation for Statistical Computing, Vienna, Austria) using the *mgcv* package version 1.8-31 and *dlnm* package version 2.4.2.

3.4 Translation and Dissemination

The added focus in this project, on translating and disseminating the research work undertaken, arose out of a need to ensure that key knowledge brokers and end users are able to grasp the results and takeaways clearly and concisely at a policy and personal level. The need for this is evident in India given the state of understanding of the health effects of air pollution among policymakers and the general public including sensitive populations. For the purposes of this particular project, we focus on specific groups under the broad umbrella descriptors of knowledge brokers and end users.

3.4.1 Informing knowledge brokers for effective policymaking

Knowledge brokers in the context of the FHI 360 framework refers to those who "help communicate evidence and facilitate evidence use between producers and end users" (Kim et al., 2018). In our case, we group three broad institutions under this category – the media, physicians, and civil society. All these institutions have a key role in understanding, interpreting, and communicating findings of key research to end users (policymakers and the general public). Past evidence from India has shown that, while knowledge of air pollution as an issue affecting health is relatively high, there is a distinct divide between what contributes to air pollution, how it affects health, and what people talk about in public spaces (Murukutla et al., 2017). A contributor to this is how the media digests and reports information produced by the "research producers". Media coverage of air pollution in India peaks during the winter months when ambient levels reach astronomical heights due to a combination of meteorology, seasonal sources such as fireworks or farm stubble burning, and increased use of waste burning for heating. Such seasonal coverage of air pollution has led to a skewed discussion focused solely on short-term seasonal high episodic events, to the detriment of increased public understanding of the key drivers of air pollution and their consequences (A. Mehta & D'Souza, 2019). These extreme levels, often breaching 30-50x the WHO's guidelines for safe daily exposure receive national and international media exposure and are thereafter picked up by civil society groups calling for urgent action to reduce high exposures. These calls by civil society then feed into further coverage of the harmful effects of high pollution events, thereby contributing to a kind of virtuous circle focused solely on seasonal episodes between September and December. No doubt this has led to some action as noted in earlier sections, but as evident from our analyses, exposure baselines need to be brought down significantly below the median and much closer to reference levels for significant health benefits to be observed.

Physicians have a key role to play as trusted arbiters and sources of information in society. The intervention of physicians in the Indian air pollution arena has been limited but effective in messaging when they involve themselves in public discourse. However, work conducted in the last couple of years by colleagues at the Centre for Chronic Disease

Control has shown that most physicians (general practitioners, cardiologists, pulmonologists and paediatricians included) have little awareness of air pollution as a risk factor and most if not all do not speak to their patients about the risk of exposure (Manogaran et al., 2020). Much of this arises from the lack of any foundational training in broader societal or environmental risk factors in the Indian medical curriculum, but as has been seen in the global context, engaging physicians and medical bodies is key to raising public awareness, fostering the climate for change, and engendering more relevant treatment protocols for those particularly at risk (Manogaran et al., 2020).

In our work, we will be focusing on targeted communication with these knowledge brokers using issue briefs that outline key details relevant to each group. For the media, we will focus on the key findings on the study, emphasizing the importance of focusing not just on seasonal high pollution events, but reporting on the issue year-round. Noting that there were no days during our study period where exposures were below WHO daily exposure guidelines, we will emphasize that what is considered a "good air day" in Delhi is in reality contributing to significant mortality. We will also focus on the E-R curves, and their indication that small-scale actions to limit extreme exposures in winter are not sufficient to protect long-term health, and that exposures must reduce significantly to achieve concomitant gains.

For civil society, messaging has largely focused on the exposure of children and associated developmental impacts (S. Mehta et al., 2020). While this is certainly a noble cause and an emotive angle to drive change, it has come at the expense of understanding who truly dies of air pollution exposure. Our study and others like it show that mortality from air pollution is skewed heavily towards those who are older than 60, and those who have pre-existing cardiovascular or respiratory illnesses. The key causes of death from air pollution as outlined in the Sub-national burden of disease estimates indicate this with ischemic heart disease, stroke and COPD topping the causes (Balakrishnan et al., 2019; Krishna et al., 2017; Pandey et al., 2020). For this brief, we will therefore focus on the fact that there is disproportionate mortality among older adults in the study population. We will also be highlighting the key role of reducing exposures substantially in relation to E-R as in the other brief.

In speaking to physicians on this subject, we will aim to first partner with appropriate local organizations led by prominent physician opinion leaders to help promote messaging. There is benefit in having a trusted voice from their own community speaking on a matter not commonly discussed in medical fora. In our brief, in addition to the key findings, we will focus on how physicians can better deliver targeted messaging to at-risk population groups such as older adults and those with pre-existing conditions. This will include measures that these individuals can take to reduce their exposures both at home and outside their home, and what specific actions they can take on days with especially high exposure. We will also highlight for physicians the specific at-risk population groups they should be speaking to specifically about air pollution exposure.

3.4.2 Empowering end users

End users as described by the FHI framework include those that are expected to apply evidence to practice and policy, i.e., policymakers and associated stakeholders. In our case, we are expanding this definition, since the issue of air pollution goes beyond an issue of effective implementation of a specific program, and relates directly to the fundamental right to life as observed by the Supreme Court of India (Sikri, 2018). This definition of end user will therefore also include the general public. Effective information delivery is vital for them to advocate and lobby for their fundamental rights with elected officials. To empower these end users, we will be creating different documents relevant to each stakeholder group, in line with specific informational needs as outlined below.

Policymakers in India constitute both the political class and the bureaucracy, with much of the technical legwork of policy development and implementation carried out by career bureaucrats with either a generalist or specialist background, depending on their seniority and ministry of posting. With regard to environmental regulation, the Ministry of Environment, Forests and Climate Change (MoEF) enacts various laws as outlined in earlier sections, with the Central Pollution Control Board (CPCB; an autonomous agency under the MoEF) entrusted with the authority to set standards and monitor implementation. While the MoEF consists primarily of generalist bureaucrats who are members of the Indian Administrative or Forest Services, the CPCB is staffed primarily by technical staff including environmental engineers and atmospheric scientists.

Standards set by the CPCB traditionally follow a set process that involves examining the existing regulatory framework, current air (or water) quality relevant to the specific standard, technological and financial feasibility of interventions, and potential health impacts (Varma et al., 2016). In prior work conducted by my colleagues and I at the Public Health Foundation of India and the Centre for Chronic Disease Control, we aimed to understand whether the health portion of this process is actually followed, and if so, what role it plays in final decision-making with respect to these standards. We found that with respect to the National Ambient Air Quality Standards (NAAQS), across the Central and eight State Pollution Control Boards, nobody has a real understanding of how and if at all health was a factor in this decision-making. Since there is no formal documentation available for the deliberations undertaken before the announcement of the revised NAAQS in 2009, there is no clarity if at all there were any evidence of the health impacts were taken into consideration during deliberations around the new standards. Additionally, we learned that given their backgrounds primarily as environmental engineers and atmospheric scientists, most if not all staff members had no understanding of the health effects of air pollution exposure, with ignorance and disinformation predominant (Bahuguna & Krishna, 2020).

This lack of understanding of the health effects of air pollution puts Indian environmental policymaking at a significant disadvantage. Unlike the established processes followed in the US or EU, with extensive scientific reviews conducted before establishment or revision of standards, the ad-hoc process followed in India, that excludes health practitioners and scientists from decision-making, ensures that standards and policies are not aligned with the public health need. To remedy this, there needs to be greater engagement with members of the CPCB and MoEF in aiding their understanding of epidemiological evidence such that any new data that arises – modelled or measured – is not dismissed out of hand for lack of understanding (Krishna, 2017, 2019). Most researchers publishing in this field generally have very little direct contact or engagement with policymakers. Instead, most of this work is presented to policymakers through media reports of the published work, as in the case of the GBD and other such large-scale studies. This leads to the reflexive defensiveness previously noted (Krishna & Reddy, 2018).

To ameliorate this, researchers will often engage with policymakers on the key aspects of their study, in advance of the journal article being released. Ideally, this would be a process owned and driven by the Government in a transparent manner involving various stakeholders, as in the case of the periodic scientific reviews undertaken by agencies like the EPA in the United States. In the absence of such formal mechanisms, however, the responsibility for effectively translating this evidence to policy relevance lies with academics.

In our brief designed for policymakers, we will aim to simplify the epidemiology of our work and focus on the key findings relevant to immediate policy and practice – namely the need to reduce exposures considerably, and the need to potentially revise the NAAQS given the significant mortality averted by meeting WHO guidelines. We will also aim to emphasize the value in shifting from a seasonal, episodic, and event-centric policymaking approach, given the marginal benefits of decreasing only high seasonal exposures. Instead, we will aim to refocus the agenda towards a policy that sets longer term goals for substantial exposure reductions with clear policy actions across the spectrum of sources to achieve these reductions.

For the public, we will be generating two infographics, one more general and one specifically aimed at school children. The latter will be disseminated through the network of schools in Delhi associated with a non-profit I co-founded, called “Care for Air”. Drafts of these infographics will be presented at the time of the OFE, with final designs made as the date of the article publication nears.

4. RESULTS

4.1 Summary Statistics:

Between June 2010 and December 2016, there were 700,512 non-accidental deaths across the four municipal corporations for which we have data. The median non-accidental deaths per day were 288 (IQR: 258, 320), median 2-day average $PM_{2.5}$ exposure was 90.7 $\mu g/m^3$ (IQR: 70.1, 126.2), and the median age at death was 60 (IQR: 40, 72). There was high variability in $PM_{2.5}$ exposure across seasons, with the minimum recorded exposure being 27 $\mu g/m^3$ (higher than WHO guidelines for daily exposure), and the maximum being over 10 times levels considered safe. Summary statistics of other meteorological variables and breakdown of key variables by strata are provided in Table 2 below.

Table 2: Descriptive Statistics

Variables	Median	Min	25th %ile	75th %ile	Max
$PM_{2.5}$ Exposure					
Daily exposure (µg/m^3)	91.1	21.4	68.9	126.2	276.7
Weather Conditions					
5-day average Temperature (°C)	25.7	8.4	17.8	28.5	36.9
5-day average Relative Humidity (%)	69.3	9.2	54.6	80.1	98.3
Daily Deaths (Count)					
Overall	279	88	252	308	485
Age Strata (years)					
>60	136	37	118	159	274
40-59	74	18	64	83	144
<40	68	29	60	76	132
Sex*					
Male	148	32	132	167	277
Female	94	21	83	107	169
Age at Death					
Overall	60		40	72	
*Analyses restricted to East, North and South Delhi Municipal Corporations					

4.2 Regression Results:

Table 2 presents the increases in relative risk of mortality for every 25 µg/m^3 increase in $PM_{2.5}$ exposure overall across the entire dataset as well as among the various strata we examined. Overall, we observed a 0.8% (95% CI: 0.3, 1.3%) increase in non-accidental mortality with every 25 µg/m^3 increase in exposure. There was significant heterogeneity across age groups with every 25 µg/m^3 increase in exposure contributing to a 1.5% (95% CI: 0.8, 2.2%) increase in mortality among those aged 60 or over, and a 0.3% (95% CI: 0.1, 0.5%) increase in those aged between 40 and 59. A significant effect was also observed in both males and females, with each 25 μg/m^3 exposure increment contributing to 0.9% and 0.7% increase in mortality, respectively. There was a large negative effect observed in those under the age of 40, and this population sub-group was therefore excluded from the final analyses presented below, with detailed information on effect estimates and exposure-response for this group presented in table 7 of the appendix. Detailed results are provided below in Table 3. A plot with effect estimates and 95% CIs are also presented in figure 3.

Table 3: Relative risk change for every 25 μg/m^3 increase in $PM_{2.5}$ exposure

For 25 μg/m^3 increase in $PM_{2.5}$ exposure	
Group	**Relative Risk (95% CI)**
Overall	**1.008 (1.003, 1.013)**
Age Strata	
>=60	**1.015 (1.008, 1.022)**
40-59	**1.003 (1.001, 1.005)**
Sex*	
Male	**1.009 (1.002, 1.015)**
Female	**1.007 (1.005, 1.010)**
*Analyses restricted to East, North and South Delhi Municipal Corporations	

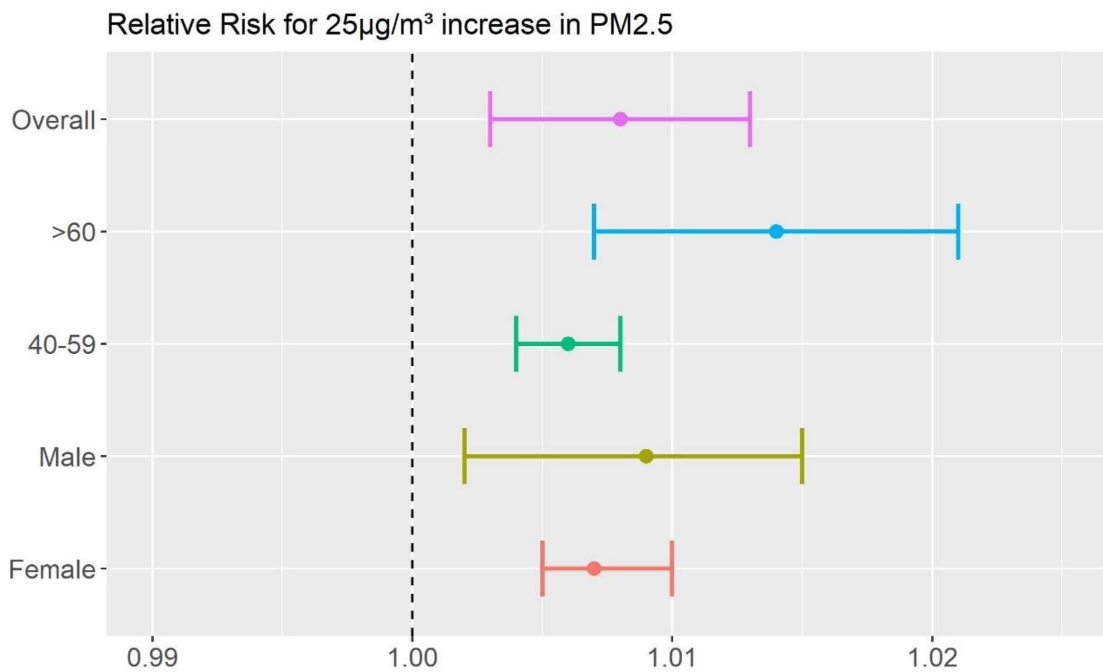

Figure 3: Relative risk change for every 25 µg/m^3 increase in $PM_{2.5}$ exposures

4.3 Exposure-Response

The overall exposure-response (E-R) relationship showed a steep increase in risk below 75 µg/m^3, reduction in slope between 75 and 125 µg/m^3 and tapering off thereafter as shown in Figure 4. This exposure-response relationship was mirrored in the over 60 and 40-59 age strata (figure 5). Both males and females showed a rapid increase in risk below 125 µg/m^3 albeit at different scales of risk, with E-R curves differing beyond that level of exposure. There was significant heterogeneity in exposure-response across seasons with winter and spring showing increasing risk throughout the exposure range (fig. 6b in appendix).

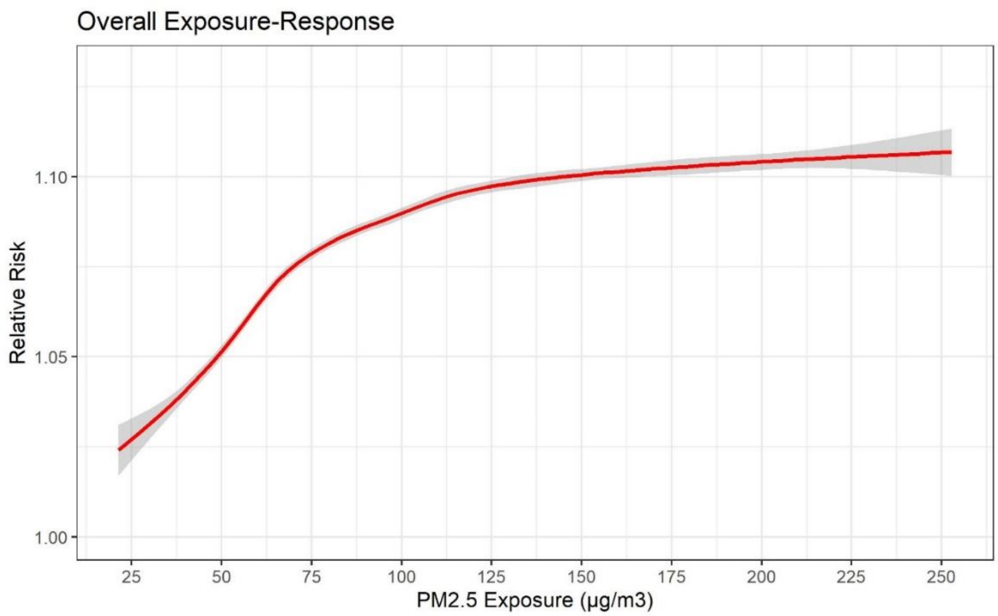

Figure 4: Exposure-response relationship among the entire study population

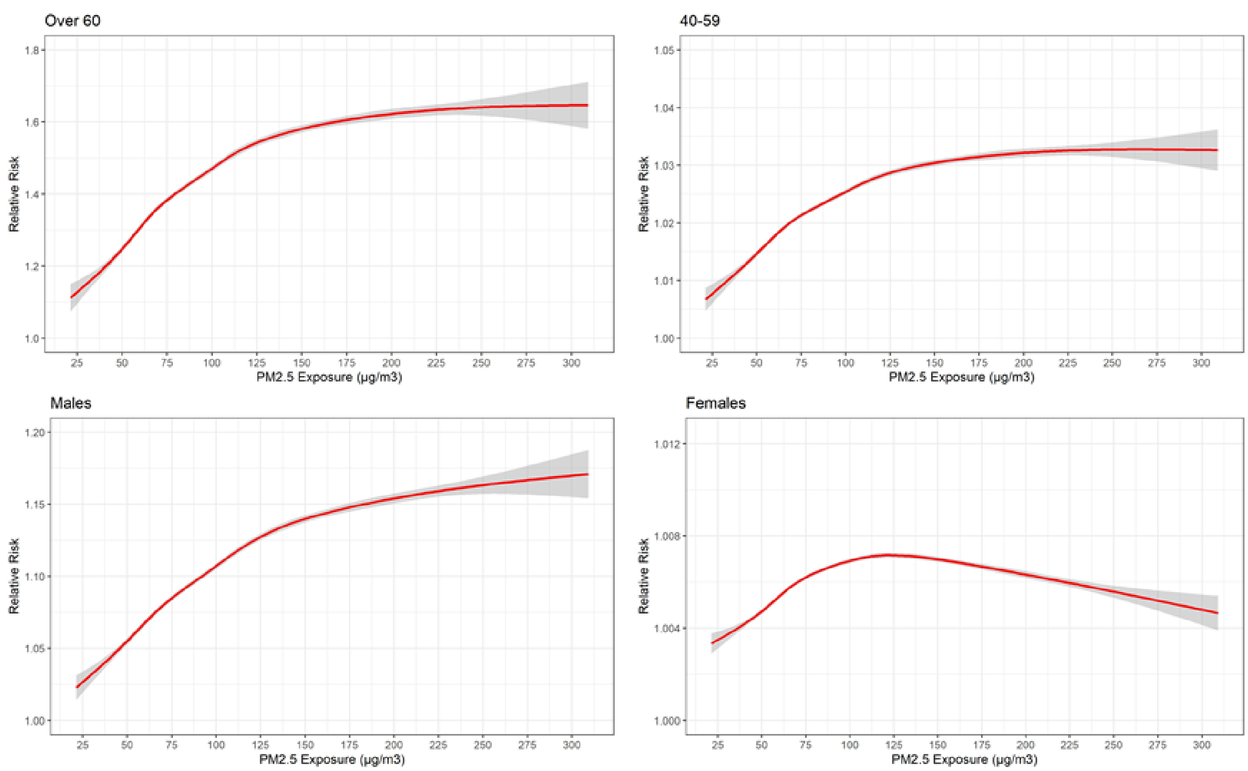

Figure 5: Exposure-response relationship among different strata

4.4 Effect modification

We analysed effect modification by temperature using interaction terms. When introducing either a linear temperature term (as a thin plate spline in interaction with the exposure), or as a categorical term in interaction with the exposure, we did not observe any effect modification by temperature. We also tested effect modification by season of death using a categorical variable for season in interaction with the exposure of interest. We observed differing E-R curves across different seasons with winter and spring showing an upward slope across the entire exposure spectrum, while summer showed an upward slope for exposures below 100 μg/m^3 (fig 6b in the appendix). We introduced different degrees of freedom for the natural spline of time to control for long-term trends and seasonality but observed no significant changes in E-R.

4.5 Potential mortality displacement

To understand the negative slopes we observed for the under-40 age category, we conducted analyses to examine whether there was a harvesting effect at play. Harvesting, or mortality displacement occurs when high-risk groups (such as the elderly or those with pre-existing conditions) in a population experience an increase in mortality in the short-term relative to healthy subjects in a population due to an external factor such as air pollution exposure (Basu, 2009; Schwartz, 2001). In our case, we hypothesized that there would be heightened risk at shorter lags of exposure with risk declining thereon. We examined the $PM_{2.5}$ exposure-mortality association over an increasing lag time up to 30 days using the DLNM approach outlined by Bhaskaran et al., (2013). This showed heightened risk at shorter lags with risk declining there-on, indicative of 'harvesting' or short-term mortality displacement for the whole population, but not specifically for under-40s. Our second hypothesis was that high-risk subjects were likely to die at lower ambient concentrations of $PM_{2.5}$, with healthier subjects remaining largely unaffected, causing a sharp increase in risk at lower exposures, with either a tapering off or even an inverse slope thereafter. If misread, these inverse slopes could be construed as conferring a protective effect with rising levels of air pollution, which we know it does not. We therefore explored the potential for a harvesting effect by examining only days under the median exposure of 91 $\mu g/m^3$. These analyses did not reveal any significant change in E-R for the under-40s (fig 6a in appendix).

4.6 Mortality averted by reducing exposures

To calculate the mortality averted by improving ambient air quality by 25 $\mu g/m^3$, we utilised the approach followed by Dominici et al., (2006) where M or attributable mortality is defined as $M = (\exp(\beta * \Delta x) - 1)*N$, with β being the RR estimate for a 1 $\mu g/m^3$ increase in 2-day average $PM_{2.5}$ exposures, Δx being 25 $\mu g/m^3$, and N being the total number of deaths in a defined time period (or for the specific sub-category). Table 4 below lists the annual reduction in deaths with a 25 $\mu g/m^3$ reduction in exposure across different strata for the year 2016. Our estimates showed the highest risk population being those over the age of 60 years, and this is reflected in the potential mortality reduction, with a 25 $\mu g/m^3$ reduction in exposure over the entire study period potentially averting 7,697 (95% CI: 6,788, 8,607) deaths among that age group.

Table 4: Averted mortality for every 25 µg/m^3 reduction in exposure

Group	Total Deaths	Reduction in deaths over study period for 25 µg/m^3 reduction in exposure (95% CI)
Overall	700,512	5,474 (2120, 8812)
>=60 years	349,473	5,113 (2856, 7357)
40-59 years	183,196	598 (198, 997)
Male	373,983	3,166 (753, 5564)
Female	234,362	1,723 (2243, 1201)

We also estimated the potential mortality averted if exposure levels were reduced from the median of 91 µg/m^3 to reference levels such as the WHO guidelines for safe exposure and the National Ambient Air Quality Standards for safe exposure. These results are presented below in table 5.

Table 5: Deaths averted over study period by reducing exposure from the median exposure (91.1 µg/m^3) to reference levels

Group	WHO - 10 µg/m^3 (95% CI)	NAAQS - 40 µg/m^3 (95% CI)
Overall	17,526 (6837, 25589)	10,983 (4297, 17501)
>= 60 Years	16,202 (9138, 23081)	10,111 (5725, 14346)
40-59 Years	1,928 (641, 3204)	1,212 (403, 2011)
Male	10,127 (2433, 17622)	6,344 (1530, 10996)
Female	5,519 (7161, 3862)	3,460 (4483, 2424)

Reducing the exposure from the median of 91.1 µg/m^3 to the WHO guideline level of 10 µg/m^3 would have averted 17,526 (95% CI: 6837, 25589) deaths (approx. 7 deaths a day) among the entire study population, with the vast majority of averted mortalities observed among the elderly population, and largely among men. Similarly, reducing exposure from the median to the NAAQS for 24-hour exposure of 40 μg/m^3 would have averted 10,983 (95% CI: 4297, 17501) deaths during the course of the study period (approx. 4.5 deaths per day).

From the exposure-response relationships generated as part of this study, it is evident that the risks posed are non-linear in nature, requiring interventions that aim to achieve reductions in ambient $PM_{2.5}$ that are far below the current median and even below those of the NAAQS. Additionally, it is also clear that the effect is heterogenous across age strata, and therefore the increased risk to sensitive groups must be taken into effect in planning appropriate interventions. Consequently, exposures must be reduced significantly from current levels to ensure appropriate reductions in risk especially to susceptible populations.

4.7 Analysis of epidemiological findings

This study is one of the first to examine the effect of $PM_{2.5}$ exposures on daily mortality in an Indian setting (Gordon et al., 2018; Singh et al., 2021). We found in our analyses a strong association between changes in $PM_{2.5}$ exposures and increased mortality in Delhi, with the effect being far stronger in older adults compared to the younger age groups. There were also heterogeneities in effects across sex. Exposure-response for the overall study population indicated a rapid increase in risk at lower exposures with a tapering off at levels above 125 μg/m^3. Similar heterogeneities were observed across other strata of interest.

Overall, while the effects on mortality in our study population were significant, they were smaller in magnitude than those reported in previous studies conducted in western settings (Aga et al., 2003; Samet et al., 2000; Zanobetti & Schwartz, 2009; Zeka et al., 2006). For a 10 μg/m^3 increase in $PM_{2.5}$ exposure, we estimated a 0.31% increase in non-accidental mortality which was comparable to results from a multi-city study conducted in China in 2016 that reported a 0.22% increase in total mortality for each 10 μg/m^3 increment in exposure (Chen et al., 2017). Our estimates were lower, however, than those of a multi-city study conducted in the US which estimated 1.18% increase in total mortality with each 10 μg/m^3 increase in 2-day average $PM_{2.5}$ exposure (Zanobetti & Schwartz, 2009).

The perceived weaker effects of $PM_{2.5}$ in our study when compared to those conducted in Europe or the US may be attributable to several factors. First, various source apportionment studies conducted in Delhi have shown that the composition of $PM_{2.5}$ in the city comprises a large proportion of crustal material from road and construction dust, wind-blown mineral dust, and other sources (ARAI & TERI, 2018; Guttikunda, 2016; Sharma & Dikshit, 2016). These proportions are comparable to those observed in several Chinese cities, but much higher than in European or American cities (Chen et al., 2017). While for the purposes of this study, we maintain the EPA principle of $PM_{2.5}$ equitoxicity, it is likely that the relative lower toxicity of crustal material may have contributed to our lower estimates.

Second, the E-R observed in our study indicated a plateauing of risk above 125 μg/m^3 of $PM_{2.5}$. A similar saturation effect was observed in Chinese studies as well (Chen et al., 2017). Analysing the E-R across different strata also showed significant heterogeneity with those below the age of 40 years showing no effect on mortality. When we examined whether this was a by-product of mortality displacement or harvesting, we did not observe any evidence of this, with the E-R for the under-40 age group remaining negative in slope (fig 6a in appendix). We also observed in our study differences in effect magnitude between males and females, which may be attributable to varying levels of outdoor activity, profession, and therefore differing exposure levels to ambient $PM_{2.5}$.

Our results hold several important findings of significance to public health. First, our finding that vulnerability to short-term $PM_{2.5}$ exposures is much higher in individuals above the age of 60 is consistent with other studies conducted around the world (Chen et al., 2012; Dai et al., 2014; Zanobetti & Schwartz, 2009) and indicates the need to deliver tailored messaging to protect this vulnerable sub-group.

Second, the heterogeneity in effect across different age groups and sexes indicates the need for targeted interventions that reduce exposures based on pre-existing risk profiles, modes of exposure (e.g., profession), and time spent outdoors.

Third, the E-R curves show us that risk rises most rapidly at lower concentrations, tapering off at levels above 125 $\mu g/m^3$. From a policy perspective, it is vital therefore that a roadmap to improve ambient air quality be not only focused on the extreme exposure events of winter, but also on those closer to the median exposure of 91.1 $\mu g/m^3$ experienced throughout most of the year. Additionally, the targets for improvement in air quality must also be commensurate to the added risk, which in this case would mean achieving WHO guidelines for safe exposure.

Fourth, the absence of an effect on mortality for those under the age of 40 does not indicate that air pollution is not harmful to this population sub-group. Indeed, the wealth of evidence from India and elsewhere showcases the harmful effects of exposure on morbidity for children and young persons (Pandey et al., 2020), and the only inference that can be drawn from these results is that young persons are not dying from short-term changes in exposure and that they may be more affected by longer term exposures.

As one of the first studies examining the acute effects of $PM_{2.5}$ on mortality, our study would hopefully not be the last. Differing $PM_{2.5}$ exposures and compositions in different parts of the country necessitate the generation of more local evidence, and as such, the findings of this study are not generalizable to the rest of the country. Our study does however have the strength of being based on a large pool of data, which allowed the study to have more than adequate power to estimate the effects observed.

Our study did also have some limitations. First, given the use of a city average $PM_{2.5}$ metric as our exposure, there is likely to be some non-differential exposure misclassification which may lead to an underestimate of the association. Second, the quality of "cause of death" coding made it impossible for us to undertake analyses by cause of death. There is also a lack of clarity on how these raw "cause of death" codes are cleaned and analysed before being published as part of annual "cause of death" statistics. Third, our model did not generate predictions for other pollutants, and we were therefore unable to include additional variables for Nitrogen or Sulphur Oxides in our models. Finally, we did not have information on the sex of the individual for one of the four municipalities, which meant the stratification of our analyses by sex was limited to 3 of the 4 municipalities.

4.8 Translation of our findings

In earlier sections, I have described in detail the methods chosen to translate and disseminate the findings of this study. Much of it, in addition to the generation of new communications material, originally involved the holding of in-person meetings with key stakeholders and the organization of dissemination workshops. The plans for these specific dissemination strategies were laid before the onset of the Covid-19 pandemic, and given the change in landscape since then, there have been revisions made with the approval of my committee. Since the pandemic-induced challenges have resulted in a delay in the manuscript of the research work being submitted, the timeline of several of the dissemination aspects has also shifted.

As a result, and as approved by the doctoral committee in April, the translation aspects discussed in this report will speak to the development of the materials themselves, and a tentative timeline for future activities viz. dissemination. As it stands, the manuscript has been submitted to an academic journal and is under review. As the manuscript review process progresses towards publication and release, we will be implementing several phases of the dissemination strategy. With a tentative timeline of September 2021 for the release of the manuscript, we will have all the materials for dissemination (issue briefs and infographics) ready well in advance. Subsequently, we will begin engaging various stakeholder groups from two months prior to the journal article publication, through the winter months.

Policymakers, a key demographic with whom we are keen to build trust in advance of the study's release, have been a challenge to access, given the ongoing pressures of the pandemic. To ensure we do not compromise on the key goals outlined earlier for this group, we will begin engaging with policymakers from different relevant government departments two months in advance of the article release. Potential actors to engage with include bureaucrats from the Central Ministries of Environment, Forests and Climate Change, Health, and Urban Development (under whom a large proportion of the administration of Delhi falls). In addition, we will also aim to engage with State and Municipal actors who have more focused day-to-day responsibilities when it comes to air pollution management in the city of Delhi. With guidance from Prof. K. Srinath Reddy and Prof. D. Prabhakaran (host organization supervisor), we will arrange informal conversations with relevant officials at these departments to explain in detail the data used, methods employed, and results obtained, with a specific focus on the utility of the study results, viz. policy going forward.

Once sensitization of policymakers is complete, we will begin to brief civil society and media stakeholders 15-20 days prior to the publication of the journal article. Foci in these conversations will be answering key questions on epidemiological aspects of the study (including distinguishing between modelled and measured data), clarifying issues around the mortality differences between age and sex strata, and most importantly emphasizing the need for large decreases in exposures given the magnitude of attributable mortality being observed. Also likely to be discussed is the need to transition from an event-centric, seasonal approach to air pollution mitigation, towards a more holistic, long-term plan to reduce ambient air pollution. There are indications that such long-term plans could crystallize under the National Clean Air Program (NCAP), but the targets of 30% reduction from current baseline by 2030 are well below what is necessary given the evidence presented here. I expect there to be high interest in the findings of this study, given the "body count" aspect of the results, the first of its kind for Delhi, and the timing of the study release relative to the high episodic pollution events observed later in the year.

Finally, post-publication, we will release infographics for the general public through social media channels of the Public Health Foundation of India and Centre for Chronic Disease Control. We will also release the targeted infographics aimed at school children through the Care for Air network of student ambassadors.

5. REFLECTIONS

5.1 Policy Relevance

As noted in earlier sections, policymaking around air pollution in India (largely focused on Delhi) has been ad-hoc and driven more by the judiciary than by the executive. This has resulted in a policy landscape that is focused more on headline management in the winter months, which have high episodic exposures, than any real sustained efforts aimed at reducing exposures year-round. In just the last 6 months, the Government of India, in response to a Supreme Court ruling, disbanded the EPCA (responsible for implementation of air pollution directives in the NCT of Delhi), replaced it with a "Commission on Air Quality Management" that was tasked with managing the regional airshed, and promptly thereafter shut this Commission down, noting that this job was already being done by relevant government departments (Pillai & Nandi, 2021). This has led to rightful public outrage given the decades of inaction observed (Dutta, 2021; Harish, 2021). At this crucial juncture, India is also revising its National Ambient Air Quality Standards (NAAQS), and is considering revamping its entire portfolio of environmental laws, perhaps with a view to dilute regulatory oversight (Nandi, 2021a, 2021b).

At this crucial juncture, the release of data quantifying for the first time the vast mortality burden from "real" data in Delhi would serve as a marker for policymaking in a way modelled estimates have not in the past. The availability of averted mortality numbers from meeting reference levels of ambient air quality, the futility of marginal reductions in winter loading compared to sustained overall reductions in air pollution, are all laid out clearly from our findings. Coupled with the targeted outreach we plan to undertake, there is potential in these findings to drive real policy change. As the Government dallies with mining regulations and delays further the implementation of thermal power standards (Aggarwal, 2021; Das, 2020), the quantification of the mortality burden in Delhi from $PM_{2.5}$ exposures, primarily observed in those within the age group of the average senior policymaker/bureaucrat and media editor living in Delhi will make the otherwise ephemeral understanding of air pollution a true lived experience.

5.2 Relevance of the work to the host organization

My study at the Chan school was partly funded through a National Institutes of Health grant awarded jointly to the Public Health Foundation of India and Centre for Chronic Disease Control in New Delhi, and the Chan School in Boston. The goals of this grant were to further research and training on air pollution epidemiology in India through joint work on the health effects of air pollution in Delhi and Chennai, and the training of a cadre of young researchers at Harvard who would carry on the work in India. As a beneficiary of support from this grant mechanism, my doctoral project work feeds directly into the goals of the project by advancing the evidence base for air pollution and health in India. It also advances the goals of the Centre for Chronic Disease Control as the organization continues to build its portfolio of work in environmental epidemiology.

5.3 Relevance of the framework for change

While conceptualizing this project, it was a challenge to choose the appropriate framework for change. Much of the work undertaken in the DrPH program with regard to the core competencies of leadership, management, communication, and innovation focuses on frameworks relevant to an organizational perspective, and not enough on enabling large-scale policy change. The handful of examples and smattering of associated frameworks we studied did not seem appropriate to provide the theoretical underpinning for a project that aimed to cover the ground that both a traditional research-centric PhD, and a translation-oriented DrPH would cover. Sustaining a piece of work from initial conceptualization to data collection, analysis, publishing, translation, and dissemination is traditionally not all carried out by academics. I chose and used the FHI framework for the very reason that it was the only one that aimed to capture, based on established practice, the pathways for an organization or an individual to use to traverse this complicated route straddling science and policy.

The framework provided a useful checklist of all the aspects of the work I needed to consider as I planned out the project. However, it was designed for a health systems paradigm in which the study, analysis and translation of scalable, targeted innovations was key. Given the inter-disciplinary and cross-sectoral nature of air pollution and how it affects health, this required some re-interpretation of certain aspects of the framework to make it more relevant to this work.

In planning for this project, I considered other frameworks including the Kingdon "Multiple streams model" which, while relevant to theorize potential policy interventions and map out the various actors involved, was not ideal for the proposed work. Reviewing the various frameworks used throughout the DrPH program also revealed to me that while there is considerable focus on the leadership aspects relevant to reforming the self, managing teams, and engendering organizational change, there is little focus on the process of “evidence to policy”. I had several discussions with faculty members on this very subject through formal and informal conversations. What would be useful for those students not focusing solely on organizational aspects would be to have greater breadth of learning on the process of evidence-to-policy translation and large-scale change.

5.4 Barriers

At the start of this project early in 2020, I anticipated about 9 months would be needed to complete all the work outlined including the translation and dissemination aspects. Then Covid-19 entered our lives, and from the initial transition to online instruction to my subsequent move back home to India (which was delayed by 3 months), it has been a tremendously challenging experience. No doubt several others have had a much harder time due to the pandemic, but the loss of family and friends to the disease, the challenge of carrying out work in the absence of support from colleagues and friends, being isolated in a time-zone 9.5 -10.5 hours ahead of Boston was one I never imagined I would be faced with. While colleagues in India have been supportive through this process, the loss of the academic community in Boston has been deeply felt. Questions I could have found answers to through a simple five-minute conversation with more experienced colleagues took me days or even weeks to understand myself. While this was certainly a fantastic learning experience in retrospect, the process of it and the challenge of not having an academic support structure was a significant barrier to progress.

The pandemic also had several other impacts on the progress of this work. It became almost impossible to engage meaningfully with key stakeholders in government given their workload and the inability to meet in person. While this may seem trivial in the context of a world that has shifted all work virtually, building trust with individuals who have little time for you otherwise requires face-to-face engagement from my personal experience. The delays to the manuscript development also led to a reframing of the goals of the project, later approved by my committee to ensure that the work would carry on post-submission of the doctoral project.

6. CONCLUSION

This project aimed to approach a complex and contested issue in air pollution and health in India from the perspective of generating new knowledge and translating that knowledge into relevant material for policymakers and citizens. Through the various analyses undertaken, new knowledge has been generated around the association of mortality with short-term PM2.5 exposures in Delhi, a city faced with a high and still rising air pollution problem. We also learned of the variable effects across different age and sex strata, with the elderly particularly vulnerable to the harmful effects of air pollution in the short-term. Meeting WHO levels for safe exposure to PM2.5 compared to our median exposure during the study period would have averted over 17,000 premature deaths, primarily among those aged 60 or over. We also learned that current policy measures to address exposures are nowhere near sufficient given the non-linear nature of exposure-response.

The implications for policy from this study are clear – $PM_{2.5}$ exposures are extremely high and to adequately protect the most vulnerable in society, exposures must reduce rapidly and significantly. Policymaking on air pollution must also eschew the short-term ad-hoc approach around high winter exposures currently *en vogue* and must aim longer term a systematic approach with time-bound, measurable targets. Additionally, there are relevant findings from our work for practice in the medical field, with physicians most in need of sensitization regarding their high-risk patients and their vulnerability to PM2.5 exposures.

Translating and disseminating this work will simultaneously be a challenging and rewarding experience given the novel approach being undertaken as a means of building trust with key stakeholders. If successful, this approach could prove useful not just in the communication of environmental risks, but more broadly around research-to-policy translation.

In the year that a global pandemic has taken over our existence and cost millions their lives, we must recognize that yet another silent pandemic rages in India, that of air pollution. Many more people will die in India this year from air pollution exposure than from Covid-19. To confront this pernicious threat, we must approach it with the same determination and speed we applied to the pandemic. If not, the promise of India's demographic dividend will prove to be a false one.

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APPENDIX 1: Supplementary materials from Aim 1

Table 6: Total deaths across the study period and in different categories

Year	Overall	>=60 Yrs	40-59 Yrs	<40 Yrs	Male*	Female*
2010 (Jun-Dec)	53,726	24,341	14,274	15,030	27,968	17,253
2011	93,058	44,945	24,141	23,930	49,154	31,122
2012	97,491	48,444	25,315	23,647	51,372	32,706
2013	106,002	52,810	27,665	25,402	56,945	36,137
2014	109,399	55,472	28,694	25,192	59,053	37,526
2015	114,753	57,764	30,433	26,475	61,195	39,809
2016	126,083	65,697	32,674	27,406	68,296	39,809
Total	**700,512**	**349,473**	**183,196**	**167,082**	**373,983**	**234,362**

*Numbers restricted to East, North and South Delhi Municipal Corporations

Table 7: Relative risk associated with a 25 µg/m^3 increase in $PM_{2.5}$ exposure for the whole population (including under-40s age group)

Group	Relative Risk (95% CI)
Overall	**1.009 (1.004, 1.013)**
Age Strata	
>60	**1.026 (1.019, 1.032)**
40-59	**1.007 (1.001, 1.014)**
<40	0.974 (0.967, 0.981)
Sex*	
Male	**1.009 (1.003, 1.015)**
Female	**1.006 (1.004, 1.008)**

*Analyses restricted to East, North and South Delhi Municipal Corporations

Figure 6: Exposure-Response curves of different strata

6a: Exposure-response for those under the age of 40 for the complete exposure range (left) and days under the median exposure (right).

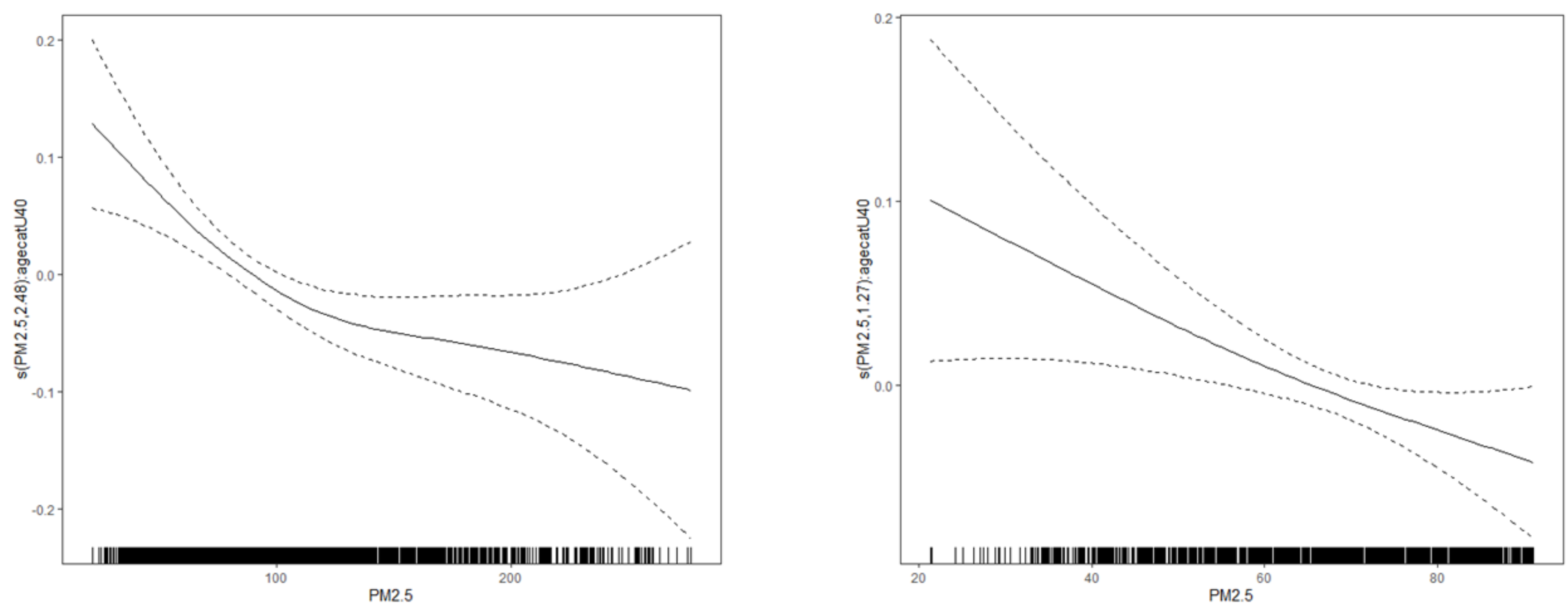

Figure 6 (continued): Exposure-Response curves of different strata

6b: By season of death for complete exposure range.