Edwards, LD; (2024) PM2.5 Exposure and Associated Health Impacts on United States Government Diplomats and Accompanying Family Members With Multiple International Relocations: Exposure Measurement and Health Modelling Study. PhD thesis, London School of Hygiene & Tropical Medicine. DOI: https://doi.org/10.17037/PUBS.04672664

DOI: https://doi.org/10.17037/PUBS.04672664

PM$_{2.5}$ Exposure and Associated Health Impacts on United States Government Diplomats and Accompanying Family Members With Multiple International Relocations: Exposure Measurement and Health Modelling Study

LESLIE EDWARDS

Thesis submitted in accordance with the requirements for the degree of Doctor of Philosophy of the University of London

March 2024

Department of Public Health, Environments & Society
Faculty of Public Health & Policy
LONDON SCHOOL OF HYGIENE & TROPICAL MEDICINE,
UNIVERSITY OF LONDON

Self-funded

Declaration

I have read and understood the School's definition of plagiarism and cheating given in the Research Degrees Handbook. I declare that this thesis is my own work, and that I have acknowledged all results and quotations from the published or unpublished work of other people.

I have read and understood the School's definition and policy on the use of third parties (either paid or unpaid) who have contributed to the preparation of this thesis by providing copy editing or proof reading services. I declare that no changes to the intellectual content or substance of this thesis were made as a result of this advice and that I have fully acknowledged all such contributions.

I have exercised reasonable care to ensure that the work is original and does not, to the best of my knowledge break any UK law or infringe any third party's copyright or other intellectual property right.

NAME IN FULL: Leslie Dawn Edwards

STUDENT ID: 154008

SIGNED: Leslie Edwards (handwritten signature removed)

DATE: March 27, 2024

Abstract

Background: Despite the established body of evidence documenting the impacts of particulate matter smaller than 2.5 µm ($PM_{2.5}$) on mortality among native populations, limited evidence is available for United States (US) diplomats and their accompanying family members, who undergo frequent relocations and dramatic changes in exposure to air pollution. US diplomats are provided air purifiers for use in their homes, and it is suspected that diplomats' personal exposure to $PM_{2.5}$, and related mortality estimated based on ambient $PM_{2.5}$, may be far lower that published literature suggests. The research described in this thesis characterizes US diplomats' $PM_{2.5}$ personal exposure while working in a highly polluted city, including an assessment of personal exposure before and after adding high-capacity air purifiers in diplomats' residences, and investigates whether US diplomats may have increased $PM_{2.5}$-related mortality in comparison to Americans who have lived exclusively in the US.

Methods: The thesis consisted of four parts. First, a literature review was conducted to identify the current evidence and research gaps regarding the health of people who relocate to an area with a different ambient air pollution level. Second, $PM_{2.5}$ personal exposure monitoring was conducted among the US diplomatic corps in a city with high ambient $PM_{2.5}$, Kathmandu, Nepal, to explore the dynamics of personal-level $PM_{2.5}$ exposure, the influence of various microenvironments and impact of added mitigation measures implemented in the diplomats' residences. A natural experiment was conducted comparing diplomats' $PM_{2.5}$ exposure and microenvironments associated with $PM_{2.5}$ exposure before (September 2019 to February 2020) and during (March to June 2020) the period when COVID-19 lockdown orders were in place. Third, an intervention study was conducted comparing diplomats' $PM_{2.5}$ exposure before and after adding high-capacity air purifiers to diplomats' homes in Kathmandu. Fourth, using a set of pre-defined international assignment scenarios, $PM_{2.5}$ related mortality among US diplomatic corps and accompanying family members was quantified by a life table modeling method.

Findings from the intervention study were used in the model to estimate the impact of a high level of mitigation on mortality.

Results: Among 15 relocation studies identified with heterogeneous study designs, most studies suggested consistent short- or long-term adverse health effects on biological function or mortality. However, many of these empirical studies of change in exposure have design weaknesses that limit the robustness of interpretation. A natural experiment in Kathmandu during the COVID-19 pandemic revealed that ambient $PM_{2.5}$ in Kathmandu was approximately 40% lower during COVID-19 lockdown in 2020 than in the same period of the previous three years and within-person comparisons suggest $PM_{2.5}$ personal exposure was 50.0% to 76.7% lower during the lockdown than before it. The intervention study indicated that when high-capacity air purifiers were added to US diplomats' homes, the ratio of $PM_{2.5}$ personal exposure to ambient $PM_{2.5}$ decreased from 0.32 pre-intervention to 0.16 post-intervention. The health modeling results suggested that life expectancy may decrease due to ambient $PM_{2.5}$ exposure in a standard 20-year diplomatic career by up to 84 days. The use of high-capacity air purifiers in polluted cities was projected to reduce the days of life lost by up to 60% for diplomats. Alternating assignments in high and low ambient $PM_{2.5}$ cities and the use of high-capacity air purifiers may reduce the $PM_{2.5}$ exposure-related DLL. The modeling results were highly sensitive to lag assumptions and further research on outcome-specific delayed impacts of $PM_{2.5}$ exposure is needed to improve the model.

Conclusion: My research provides insights into $PM_{2.5}$ personal exposure levels variable to time, micro-environment, activity patterns, and mitigation used at home among internationally assigned US diplomats in cities with high ambient $PM_{2.5}$ and the anticipated $PM_{2.5}$ related impacts on mortality. In the high pollution environment of Kathmandu, air purifiers with home sealing provided substantial protection against ambient $PM_{2.5}$ in the home environment. Application of the health model to the US diplomatic corps indicates the magnitude of the impact of varying $PM_{2.5}$ exposure levels on diplomats'

life expectancy and the possible benefits of the mitigation measures used in diplomats’ residences and in the workplace in many highly polluted cities.

Acknowledgements

I am tremendously grateful to my supervisory committee: Dr. Ai Milojevic, Dr. James Milner, and the late Prof. Paul Wilkinson for their support and guidance. I appreciate the numerous hours we discussed options to better estimate the health impacts of exposure to fine particulate matter smaller than 2.5 µm ($PM_{2.5}$) among American diplomats. The expertise and wisdom my committee provided was crucial to developing a thorough research plan for my doctoral program. I would also like to thank Prof. Ben Armstrong for his advice on my research plan as well.

I would like to acknowledge my former colleagues at the United States Department of State including Claire Huson, Kathy McCray, Wayne Quillin, Joe Beres and Greg Martin. Claire and Joe, you were both amazing mentors on personal exposure monitoring and I will treasure the memories of our monitoring trips in India, Uganda, and Saudi Arabia forever! Thank you to the wonderful staff at the United States Embassy in Kathmandu, Nepal including Dr. Leslie Iverson, Dr. Gemma Rutter, Todd Tiffany, Durga Godar, and the entire Health Unit.

I am very grateful to Shing Lee and Laura Wilson for their support and advice on statistical analysis and your friendship for more than 20 years. Finally, thank you to my parents for their endless support and encouragement. I could not have done this without you! You often remind me that when I was a child, I said I wanted to “broaden my horizons” – thank you for helping do just that!

Table of Contents

Contents

List of Figures

Chapter 1

Chapter 3

Chapter 4

Chapter 5

Chapter 6

List of Tables

Chapter 2

Chapter 3

Chapter 4

Chapter 5

Chapter 6

List of Abbreviations

AP	Air Purifier
APT	Applied Particle Technology
aSOA	Anthropogenic Secondary Organic Aerosols
CO	Carbon monoxide
CO_2	Carbon dioxide
CI	Confidence Interval
COPD	Chronic Obstructive Pulmonary Disease
COVID-19	Coronavirus Disease of 2019
C-R	Concentration Response Function
DLL	Days of Life Lost
DM	Diabetes Mellitus
EPA	Environmental Protection Agency
FEV_1	Forced Expiratory Volume in 1 Second
FVC	Forced Vital Capacity
GBD	Global Burden of Disease
GPS	Global Positioning System
HR	Hazard Ratio
HRV	Heart Rate Variability
IAQ	Indoor Air Quality
ICD	International Coding of Disease
IHD	Ischemic Heart Disease
I/O	Indoor/Outdoor Ratio
IQR	Interquartile Range
LBW	Low Birth Weight
LRI	Lower Respiratory Infection
LRTI	Lower Respiratory Tract Infection
MMEF	Maximal Mid-Expiratory Flow

MVV	Maximal Voluntary Ventilation
NO	Nitrogen Oxide
NO_2	Nitrogen Dioxide
O_3	Ozone
OR	Odds Ratio
OSF	Open Science Framework
P/A	Personal to Ambient Ratio
PECOS	Population, Exposure, Comparator, Outcomes, and Study
PEFR	Peak Expiratory Flow Rate
POA	Primary Organic Aerosols
PM	Particulate Matter
$PM_{2.5}$	Particulate Matter with an aerodynamic diameter of <2.5 µm
PM_{10}	Particulate Matter with an aerodynamic diameter of <10 µm
PTB	Preterm Birth
RR	Relative Risk
RAP	Room Air Purifiers
SES	Socioeconomic Status
SGA	Small for Gestational Age
SO_2	Sulphur Dioxide
UFP	Ultrafine Particles
USG	United States Government
YLL	Years of Life Lost
WHO	World Health Organization

PART I: Background to the thesis

1 Introduction

1.1 Context

The association between $PM_{2.5}$ and a range of health conditions, including cardio-respiratory disease and premature mortality, is well established (Cohen et al., 2017; Rajagopalan et al., 2018). The most common causes of death attributable to ambient $PM_{2.5}$ include stroke, ischemic heart disease, (IHD) and chronic obstructive pulmonary disease (COPD) (Cohen et al., 2017). The United Kingdom's (UK) Committee on the Medical Effects of Air Pollution (COMEAP) has reported that both short- and long-term exposure to $PM_{2.5}$ can lead to or exacerbate cardiovascular disease and a shorter life expectancy (Committee on the Medical Effects of Air Pollutants, 2010, 2018). The American Heart Association (AHA) conducted a systematic review of published research examining the relationship between air pollution and cardiovascular disease and concluded that $PM_{2.5}$ exposure could lead to increased levels of IHD, ischemic stroke, cardiovascular hospitalizations, and mortality (Tsao et al., 2022). In 2019, 4.2 million deaths globally were related to ambient $PM_{2.5}$ air pollution exposure (Cohen et al., 2017; Sang et al., 2022). The 2019 Global Burden of Disease (GBD) study estimated that ambient air pollution was the seventh leading risk factor globally for disability adjusted life years (DALY) lost (GBD Risk Factors Collaborators, 2020b). The GBD study also suggested that life expectancy may be reduced by 1.03 years globally on average and by 0.37 years among persons in high income countries (Apte et al., 2018).

The US diplomatic corps is a highly mobile population with international relocations, on average, every one to four years over the course of their 20-year career with the US government. Many cities that host a US Embassy or Consulate have ambient $PM_{2.5}$ levels much higher than the World Health Organization's (WHO) recommended annual level of 5 $\mu g/m^3$ and are locations where diplomats may be assigned for multiple years (Health Effects Institute, 2023; IQAir, 2022; World Health Organization, 2021, 2022). US diplomats and family members work and live in countries all over the world, including locations with air pollution more than 10 times the level found generally in American cities (World Health Organization, 2022). Although extensive research has been published linking long-term exposure to high ambient $PM_{2.5}$ with increased mortality, little research has previously addressed how varying $PM_{2.5}$ levels, sources and composition across the globe may impact mortality and it is unclear what the health impact of varying $PM_{2.5}$ levels may be for the US diplomatic corps.

1.1.1 Change in Health Following a Change in Ambient $PM_{2.5}$

At the time this project was developed, very few prior research studies were available that documented $PM_{2.5}$ exposure and health status before and after relocation to an area with a change in ambient $PM_{2.5}$. The Children's Health Study in the US identified changes in lung function among adolescents who relocated with an inverse relationship observed between lung function and ambient PM_{10} in the new location (Avol et al., 2001). Relevant evidence is also provided from studies of changes in air pollution in single locations. For example, a study conducted among university students in Beijing, China before, during, and after the 2008 Olympics identified a decrease in inflammatory biomarkers and heart rate when the ambient $PM_{2.5}$ decreased during the Olympics (Rich et al., 2012). Within one to five weeks after the completion of the Olympics when Beijing's $PM_{2.5}$ increased but was still lower than the pre-Olympics' level, students' heart rate and most inflammatory biomarkers returned to their pre-Olympics level, while their systolic blood pressure, C-reactive protein, and one biomarker related to blood clotting were lower than the pre-Olympics levels. Findings from the Beijing study suggest that the duration, or durability, of cardiovascular and inflammatory effects experienced during a brief change in ambient $PM_{2.5}$ is unclear.

1.1.2 $PM_{2.5}$ Personal Exposure and the Impact of Time Spent in Microenvironments

Although international relocations are likely to have adverse effects on the health of US diplomats and their families due to higher air pollution exposures than those experienced in the US, it is likely that diplomats' $PM_{2.5}$ personal exposure may be lower than the city-wide average ambient $PM_{2.5}$ as recorded by fixed-site monitors. US diplomats often have access to air purifiers in their homes, highly filtered air in their workplace and other mitigation that may help to reduce their $PM_{2.5}$ exposure. A study of six US diplomats living in New Delhi, India in 2017 reported that the ratio of the mean of the diplomats' $PM_{2.5}$ personal exposure to the mean ambient $PM_{2.5}$ recorded during the corresponding time period through fixed-site monitoring was 0.20. in other words, personal $PM_{2.5}$ was 20% of the ambient $PM_{2.5}$ concentration (Huson et al., 2017). The relationship between $PM_{2.5}$ personal exposure and ambient $PM_{2.5}$ can be influenced by a variety of factors including the $PM_{2.5}$ concentration in each microenvironment, the amount of time spent outdoors, indoors at home, and in other microenvironments, as well as the building porosity, ventilation (e.g. using central air conditioning, air purifiers, leaving the windows open) and $PM_{2.5}$ generating activities conducted in indoor settings (*e.g.* cooking, setting a fire in the fireplace, cleaning) (Lim et al., 2011; MacNeill et al., 2012; United States Environmental Protection Agency, 2023b; Zhao et al., 2015) . Evangelopoulos *et al.* conducted a systematic review of $PM_{2.5}$ personal monitoring studies with ambient $PM_{2.5}$ data published and reported the estimate of the ratio of personal $PM_{2.5}$ to ambient $PM_{2.5}$ was 0.60 (95%CI: 0.46, 0.94) among 10 studies conducted in China, 0.50 (95%CI: 0.43, 0.57) for 1 study conducted in Vietnam, and 0.63 (95%CI: 0.55, 0.71) among 79 studies included in the review, regardless of geographic location of the study (Evangelopoulos et al., 2020).

Personal monitoring studies consulted in Asian cities that host a US Embassy have yielded varying results regarding the relationship between $PM_{2.5}$ personal exposure and ambient $PM_{2.5}$ levels. In a study conducted among healthy adults in Delhi, India during the winter, the mean [standard deviation] $PM_{2.5}$ personal exposure (432[230] µg/m^3) was slightly lower than the ambient (488[257] µg/m^3) $PM_{2.5}$ concentration (Pant et al., 2017). The ratio of personal $PM_{2.5}$ to ambient $PM_{2.5}$ was 0.88. Study participants used space heaters during the evening and used gas for cooking and did not use home air purifiers. $PM_{2.5}$ concentrations according to microenvironments were examined for study participants and, among indoor settings, the mean $PM_{2.5}$ measured through personal monitoring was higher in the kitchen than in other parts of the home and in participants' offices. In a study of office workers in Seoul, South Korea, $PM_{2.5}$ personal exposure was 28.5[18.4] µg/m^3 and the ambient $PM_{2.5}$ was 34.1[12.6] µg/m^3 and the ratio of personal $PM_{2.5}$ to ambient $PM_{2.5}$ was 0.84 (Guak & Lee, 2018). Study participants spent approximately 50% of the personal monitoring study period in the office and 38% at home. A study conducted among university students in Beijing reported mean $PM_{2.5}$ personal exposure (33.8[27.8] µg/m^3) and ambient $PM_{2.5}$ concentration (58.2[50.0] µg/m^3) and the ratio of personal $PM_{2.5}$ to ambient $PM_{2.5}$ was 0.58 (Lin et al., 2020). In this study, participants spent 79% of the monitoring period in their home and 16% at the university, and an examination of the time weighted personal $PM_{2.5}$ exposure attributed to each microenvironment revealed that 75% of their $PM_{2.5}$ personal exposure was acquired during time at home and 22% was acquired while in the workplace. The mean personal $PM_{2.5}$ concentration by microenvironment was lower in their home (33.8[31.5] µg/m^3) than at the university (38.9[47.7] µg/m^3), with higher concentrations reported while participants were cycling (109.8[62.4) µg/m^3), shopping (79.6[103.4] µg/m^3) or dining at a restaurant 45.4[60.0] µg/m^3). Study participants did not use air purifiers in their homes and reported using coal for heating and cooking. Boomhower *et al.* conducted a meta-analysis of 44 $PM_{2.5}$ personal monitoring studies and reported the ratio of $PM_{2.5}$ personal exposure to ambient $PM_{2.5}$ of 0.63 (95% CI: 0.55, 0.71) (Boomhower et al., 2022). The meta-analysis included studies conducted in a variety of locations and among a variety of study participants and the personal to ambient ratio is lower than that reported by Pant *et al.* in Delhi and Guak *et al.* in Seoul, but still considerably higher than that reported by Huson *et al.* among US diplomats working in Delhi.

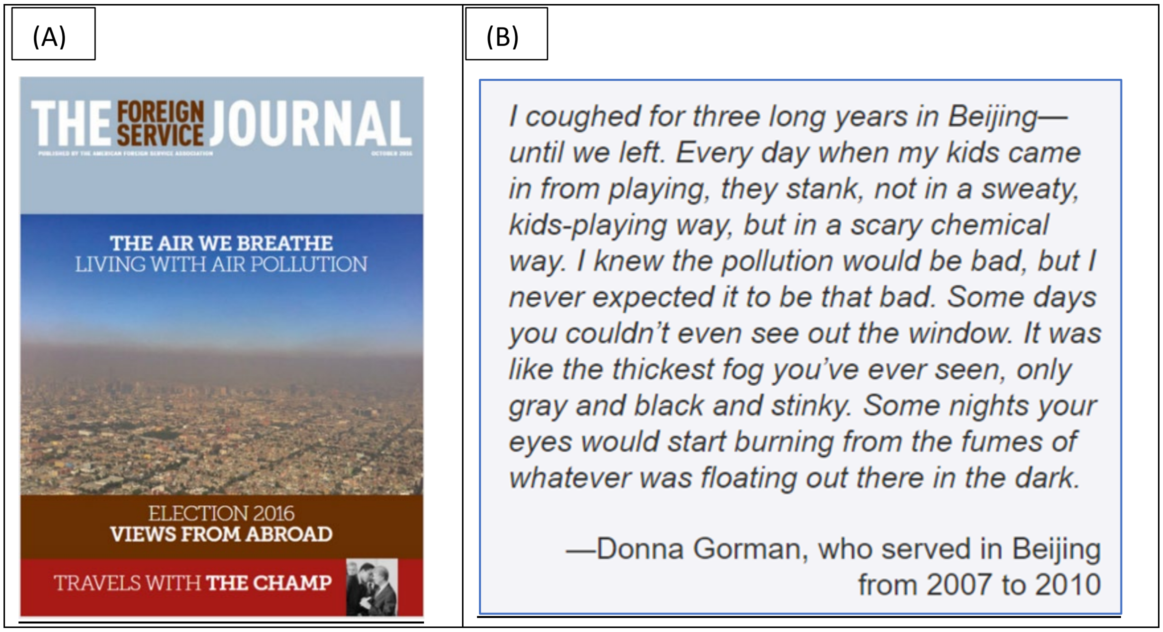
1.1.3 Impact of Air Purifiers on Indoor $PM_{2.5}$ Concentrations and $PM_{2.5}$ Personal Exposure

Prior intervention studies have reported the impact of air purifier use on indoor air quality, and in some cases $PM_{2.5}$ personal exposure, in cities with high ambient $PM_{2.5}$. A study of the impact of adding indoor air purifiers in an apartment dwelling in Beijing reported a 55% reduction in indoor $PM_{2.5}$ and a reduction in the ratio of personal $PM_{2.5}$ to ambient $PM_{2.5}$ from 0.98 pre- to 0.43 post-intervention (Deng, 2017). Indoor $PM_{2.5}$ was reduced by 57% in Shanghai university dormitory rooms when air purifiers were added (Chen et al., 2015). A long-term study in southern California in two communities with high ambient $PM_{2.5}$ reported a 48% decrease in indoor $PM_{2.5}$ following the use of a high efficiency air purifier in study participants' homes (Bennett et al., 2022). An intervention was conducted in Beijing, China among persons in seven households and revealed a 28% decrease in participants' $PM_{2.5}$ personal exposure and a 72% decrease in participants' home indoor $PM_{2.5}$ after adding one air purifier to each household (Barkjohn et al., 2020). A separate study in Shanghai among 43 children with asthma reported a decrease in the ratio of indoor $PM_{2.5}$ to ambient $PM_{2.5}$ from 0.55 pre- to 0.27 post-addition of an air purifier to the bedroom of each study participants (Brehmer et al., 2020). The ratio of $PM_{2.5}$ personal exposure to ambient $PM_{2.5}$ was similar pre- and post-intervention at 1.11 and 1.12, respectively, indicating that the change in indoor $PM_{2.5}$ in participants' bedrooms was outweighed by $PM_{2.5}$ personal exposure in other microenvironments the participant visited during the observation period. The amount of time participants spent in each microenvironment was not reported and finding suggest the importance of examining study participants' time activity patterns and to examine microenvironment specific $PM_{2.5}$ concentrations in future studies.

These results suggest that adding air purifiers to US diplomats' homes in highly polluted cities may help reduce the $PM_{2.5}$ in their home as well as reduce their $PM_{2.5}$ personal exposure, although it is not clear how applicable these findings may be to the US diplomatic corps due to possible differences in their demographics, housing quality, time-activity patterns, and use of air purifiers in comparison to the participants in the aforementioned studies.

1.2 Motivation of the PhD Research

The population studied in this PhD research is the US diplomatic corps and accompanying family members, usually children. The motivation to conduct the research occurred during my work as an Epidemiologist with the US government. From 2013 to 2019, I worked in the Occupational Health Office with the US Department of State. In this position I worked closely with US Department of State physicians and other medical professionals to better understand diplomats' health risks associated with working in highly polluted cities. It was quite common for US diplomats assigned to work in China and India, in particular, to express concern about living in those countries due to the high levels of $PM_{2.5}$. Although the exposure to $PM_{2.5}$ for diplomats and their accompanying family members is suspected to be lower than the city average, US diplomats have expressed concern to the American Foreign Service Association and asked for more information about the health implications of working in high $PM_{2.5}$ cities (Lynn, 2016; Schaefer-McDaniel, 2016) (for example, see Figure 1).



I coughed for three long years in Beijing—until we left. Every day when my kids came in from playing, they stank, not in a sweaty, kids-playing way, but in a scary chemical way. I knew the pollution would be bad, but I never expected it to be that bad. Some days you couldn't even see out the window. It was like the thickest fog you've ever seen, only gray and black and stinky. Some nights your eyes would start burning from the fumes of whatever was floating out there in the dark.

—Donna Gorman, who served in Beijing from 2007 to 2010

Figure 1: (A) The October 2016 edition of The Foreign Service Journal, a publication of the American Foreign Service Association and (B) a quote from a US diplomat who served in Beijing, China that appeared in this edition of the Journal.

While I worked at the US Department of State, numerous research articles (Chen et al., 2012; Guttikunda & Goel, 2013; Lozano et al., 2012) and general news articles (Bruno, 2013; Harris, 2015; Wong, 2013a, 2013b) were published about the levels of PM$_{2.5}$ in China and India, in particular, and US diplomats often checked in with the Occupational Health Office to discuss the health implications for them and their children if they agreed to accept a multi-year position in Beijing, New Delhi or other cities with high PM$_{2.5}$. In 2008, the US Department of State added a fixed-site ambient PM$_{2.5}$ monitors at the US Embassy in Beijing, China and has since added 72 additional fixed-site PM$_{2.5}$ monitors in a total of 55 countries (Figure 2) (United States Environmental Protection Agency, 2023a). The increasing availability of local PM$_{2.5}$ data empowered US diplomats to ask more questions about the health impacts of PM$_{2.5}$ exposure. In 2013, I began reviewing published literature on the health effects of PM$_{2.5}$ and learned that there were few published studies that studied populations with relocations with an examination of health status and ambient PM$_{2.5}$ before and after the relocation.

Figure 2: Location of US Embassy based Ambient Air Quality Monitors (n=73), (United States Environmental Protection Agency, 2023a)

1.2.1 US Diplomatic Corps Population

More than 10,000 US diplomats and family members work and live in 276 international locations that host a US government mission (United States Department of State, 2022b). The duration of diplomats' assignments, also called postings, to work in a US Embassy, US Consulate or other workspace typically located outside of the US varies according to agency, but the majority of assignments last for two to four years. Some assignments are limited to one year duration due to security concerns and these posts often prohibit staff from bringing family members. Some US government agencies allow diplomats to remain in an assignment for up to 8 years per location. Depending on the diplomat's work specialty and area of interest, they could spend the bulk of their 20 plus year career serving in highly polluted locations. Of the 229 cities that host a US government Embassy or Consulate, 61.3% have annual $PM_{2.5}$ levels greater than the US EPA's National Ambient Air Quality Standard (NAAQS) of $PM_{2.5}$ annual average (12 $\mu g/m^3$) and 96% are greater than the World Health Organization's Air Quality Guideline $PM_{2.5}$ annual average (5 $\mu g/m^3$) (United States Environmental Protection Agency, 2023b; World Health Organization, 2021). Figure 3 shows a map of US Embassies and other government offices globally as well as information about their ambient air quality.

🟢 Meets WHO standard (PM$_{2.5} \leq 5 \mu g/m^3$)
🟡 Exceeds WHO standard by 1 to 3 times (PM$_{2.5}$ 5.1 to 15.0 $\mu g/m^3$)
🟠 Exceeds WHO standard by 3 to 6 times (PM$_{2.5}$ 15.1 to 30.0 $\mu g/m^3$)
🔴 Exceeds WHO standard by 6 to 8 times (PM$_{2.5}$ 30.1 to 40.0 $\mu g/m^3$)
🟣 Exceeds WHO standard by more than 8 times (PM$_{2.5} \geq$ 40.1 $\mu g/m^3$)

Figure 3: Ambient PM$_{2.5}$ annual mean in cities hosting a US Embassy or US Consulate, data sources (GBD Risk Factors Collaborators, 2020a; IQAir, 2022)

The US government takes several measures to educate employees about the ambient PM$_{2.5}$ level in cities hosting a US Embassy or US Consulate and US diplomats and family members must be medically cleared to live in a city before the assignment begins. Medical clearance criteria include a review of diplomats' past medical history and availability of medical specialists in the assignment city that could treat any pre-existing conditions that may arise while the diplomat is posted in that city. US diplomats have the right to appeal the medical clearance ruling for themselves or their family members and, in some cases, clearance may ultimately be granted based on statutes in the Americans with Disabilities Act (US Department of Justice, 2019).

US diplomats' lifestyles vary during assignments in different locations due to security concerns, availability of recreational options, and workload, among other factors. Security is a key factor in housing selection and security experts select residences either in free standing homes or apartment buildings that have met the minimum security criteria (United States Department of State, 2022a). In many locations, security guards are located at the entry of diplomats' homes. In most cities, US diplomats can ship a private vehicle to each assignment location and can drive that vehicle as needed, however, in some locations the US government does not allow private vehicles and diplomats either ride a shuttle bus or other Embassy vehicle to work. In many cities with high $PM_{2.5}$, US diplomats are given air purifiers to use in their personal residence and the air in the US Embassy is highly filtered. Most US Embassies and Consulates have a nurse and/or a physician on staff that conduct annual preventive care examinations, provide vaccinations and can facilitate acute care hospitalizations or medical evacuations to hospitals in other countries, if needed (United States Department of State, 2020). Diplomats can choose the schools that their children attend while on international assignments and many children attend local private schools, however, in some cases children do not accompany their parent(s) on diplomatic assignments and instead remain in the US to attend school.

1.2.2 Workplace Air Quality for US Diplomats

Air quality inside US Embassies and other government offices is a concern as diplomats spend at least 40 hours per week at work. Figure 4 shows photos of the US Embassies in China, India, Nepal, and Niger and ambient $PM_{2.5}$ levels reported in the cities hosting these Embassies are amongst the highest reported among cities hosting a US Embassy or Consulate. US diplomats and accompanying family members have expressed concern about working and living in cities with high $PM_{2.5}$ and anecdotally, there were some reports of concern about workplace air quality. In 2018, US diplomats were surveyed about workplace air filtration and other air quality mitigation efforts (US Department of State, 2018a). While the overall response rate to the survey was low (44%), staff in 60% of the US Embassies and Consulates with the highest ambient air quality (annual $PM_{2.5} \geq 40\ \mu g/m^3$) responded to the survey. Workplace air quality mitigation activities among survey respondents listed in order from the most effective to least effective include use of electrostatic precipitators (29%), room air cleaners (RACs) in use in offices (3%), central air filtration with a minimum efficiency reporting value of 8 or higher (34%), and no enhanced air filtration (34%). Results of the survey indicated that workplace air qualities levels vary by location and that more information is needed to accurately describe US diplomats' personal exposure to $PM_{2.5}$.

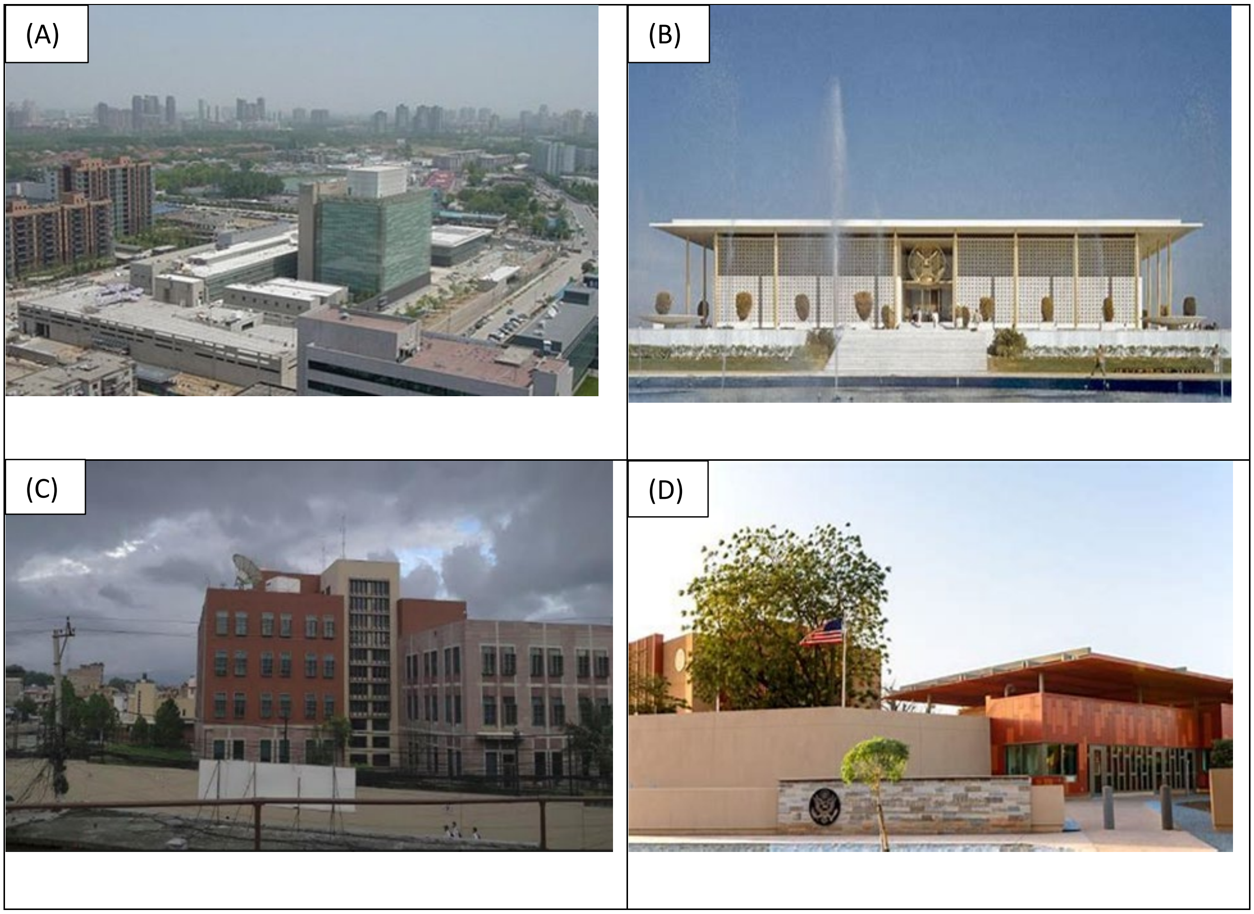


Figure 4: US Embassies in (A) Beijing, China, (B) New Delhi, India, (C) Kathmandu, Nepal and (D) Niamey, Niger (photo sources (A) https://china.usembassy-china.org.cn/, (B) https://in.usembassy.gov/, (C) https://np.usembassy.gov/, and (D) https://ne.usembassy.gov/

1.2.3 Home Indoor Air Quality for US Diplomats and Accompanying Family Members

Home air quality is of great concern when determining personal exposure to air pollution and a study of the activity patterns of more than 1700 Americans revealed that they spent on average 68% of their time at home and 19% of their time in other indoor locations including the workplace and restaurants (Klepeis et al., 2001). Prior to completing the work described in this thesis, there were no published estimates of $PM_{2.5}$ levels in diplomats' residences. Residences used by US diplomats during their assignments are typically rented but, on some occasions, they are built and owned by the US government. US Embassies use a daily $PM_{2.5}$ average of 35 ug/m^3 as a target for indoor air quality (IAQ) in personal residences, however, it is not a requirement that the IAQ be at or below this level (US Department of State, 2018b). The US Embassy in Kampala, Uganda provides air purifiers to diplomats for use in their residences and a self-administered survey of diplomats in 2017 revealed that 68% of diplomats were using the air purifiers (United States Department of State, 2018). Reported reasons for why diplomats did not use their air purifiers included perceived high levels of noise generated when air purifiers were in use, lack of clarity about when and how to change the air purifiers’ filters, and limited availability of current converters in homes; the air purifiers were 120 volts while Uganda’s electrical system was 240 volts.

1.2.4 Variation of Exposure

Ambient air pollution is not directly measured in every city that hosts a US Embassy, US Consulate, or other US government office. Measured annual $PM_{2.5}$ averages for the most recent year available, collected at fixed site monitoring stations at US Embassies and other fixed site monitors reported by the WHO, indicate a wide range of ambient $PM_{2.5}$ levels ranging from a high of 128.0 $\mu g/m^3$ in Antananarivo, Madagascar to a low of 4.1 $\mu g/m^3$ in Nassau, Bahamas (United States Environmental Protection Agency, 2023a; World Health Organization, 2022). Daily $PM_{2.5}$ exposure levels for most US diplomats are expected to be lower than that of their accompanying family members that do not work at the US Embassy or US Consulate office building, due to the high level of air filtration at most US government buildings overseas. In addition to ambient air quality and workplace air quality, other factors that influence a personal exposure level to $PM_{2.5}$ include home air quality and mitigation measures used at home, the method of commuting to work and/or other daily activities, the location of the home (and proximity to a major roadway), and the amount of time spent outdoors. Three $PM_{2.5}$ personal monitoring feasibility studies conducted among US diplomats in India, Uganda and Saudi Arabia suggested notable difference between personal $PM_{2.5}$ levels and ambient $PM_{2.5}$ levels and at daily average scale, between air purifier users and non-users at home and between US diplomats working at an Embassy building during the day and family members staying at home (Edwards L. & Beres, 2017; Edwards L. et al., 2018; Huson et al., 2017). The ratio of the mean personal $PM_{2.5}$ to the mean ambient $PM_{2.5}$ (P/A) ranged from 0.10 in India to 0.28 in Saudi Arabia. In order to improve the precision of estimates of the health risks associated with $PM_{2.5}$ exposure among US diplomats, the variation between the ambient $PM_{2.5}$ and personal exposure needs to be characterized.

1.3 Scope of My Research

My PhD research considered how frequent international relocations can affect exposure to ambient $PM_{2.5}$ air pollution for US diplomats and their families, and the resulting impact this may have on their health. To do this, it was necessary to produce and combine several types of evidence:

- Evidence on how relocations affect people’s exposure and associated health risks (given the limited previous evidence on this topic).
- Evidence to characterize the personal exposure of US diplomats living and working in a highly polluted city.
- Evidence on the potential for mitigation measures to reduce personal exposure of US diplomats.
- Evidence on the air pollution-related health risks of US diplomats and their families during and after a career involving international relocations. This final component of the research integrates the above evidence on health risks following relocations, personal exposure, and mitigation measures to better understand the additional health risks that US diplomats and their families may experience relative to if they had remained in the USA.

To generate the above evidence, the four components of my research include (1) a systematic review of the published literature on ambient air pollution and health status before and after relocation to an area with a change in ambient air pollution. The review was conducted in order to better understand existing research that may be applicable to the US diplomatic corps and to help identify health outcome(s) to be included in the health modeling study. The second (2) component of my research is a natural experiment examining the $PM_{2.5}$ personal exposure among US diplomats and accompanying family members living in a highly polluted city (Kathmandu, Nepal) before and during the COVID-19 lockdown period in 2020. This work was conducted to better understand the relationship between daily activities and $PM_{2.5}$ during the lockdown period and how they relate to pre-COVID personal exposure trends. The third (3) component is an intervention study examining the impact of added mitigation in diplomats' homes in Kathmandu on diplomats' $PM_{2.5}$ personal exposure. In this study, US diplomats were offered high-capacity air purifiers to improve the filtration of air in the home and, in some cases, diplomats also improved the air tightness of their home. I conducted this study in order to gain a better understanding of how much diplomats may be able to reduce their $PM_{2.5}$ exposure in cities with very high ambient $PM_{2.5}$ with the use of a high level of mitigation in their homes. The fourth (4) component of my PhD research includes the development of a novel model to estimate the impact of frequent changes in ambient $PM_{2.5}$, due to international relocations, on mortality. The model also examined the impact of exposure mitigation measures on the mortality estimates using results from the third component of my research, the intervention study in Kathmandu. Completion of the four components of the PhD research increased my understanding of the limited published literature examining health effects before and after relocations to areas with a change in $PM_{2.5}$, provided clarity as to US diplomats' $PM_{2.5}$ personal exposure in a highly polluted city, the impact of added mitigation at home on diplomats' $PM_{2.5}$ personal exposure, and estimated the change in $PM_{2.5}$ related mortality among US diplomats who completed a 20 year career with the US government, and lived in a variety of international cities (Figure 5).

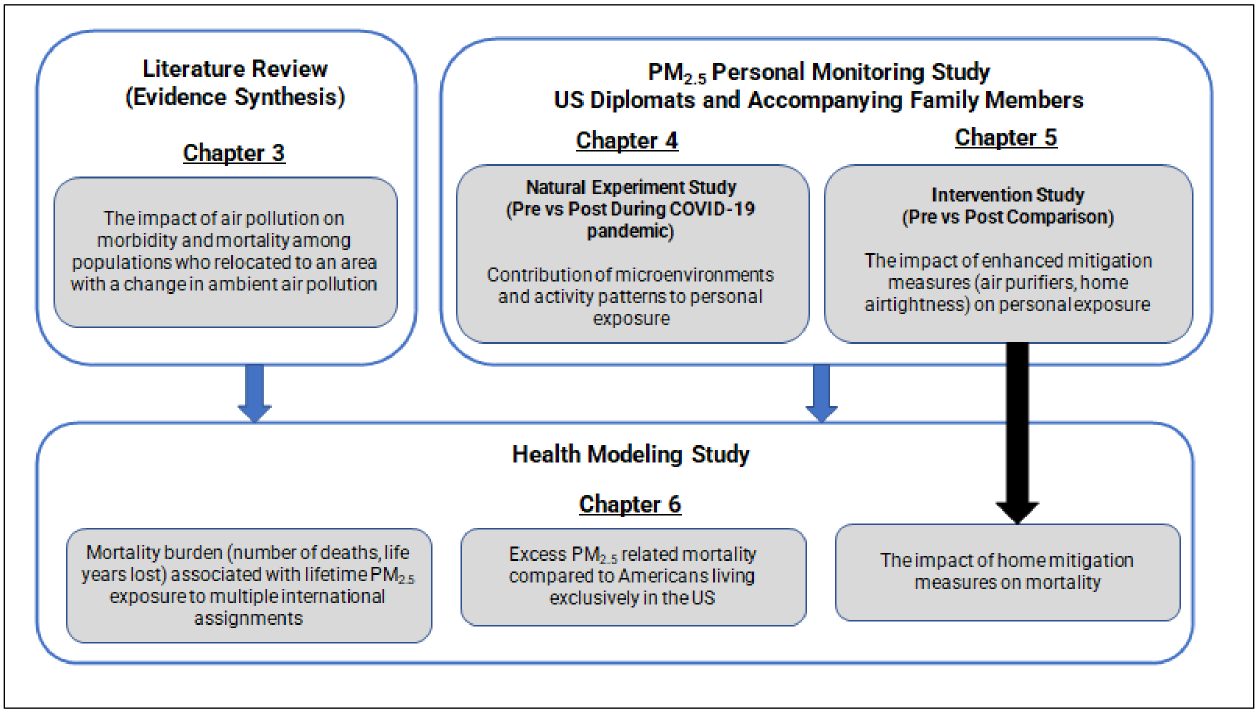


Figure 5: The four components of my PhD research that contribute to the understanding of $PM_{2.5}$ personal exposure and $PM_{2.5}$ impacts on mortality for US diplomats and accompanying family members.

Figure 5 details the relationship between thesis chapter activities and how the chapters comprise a single body of work, focused on understanding US diplomats' $PM_{2.5}$ personal exposure and mortality associated with multiple international relocations. Results from the literature review in Chapter 3 indicated changes in mortality rates among persons who relocated to an area with a change in ambient air pollution. These findings contributed to the selection of mortality for the health outcome examined in the health model in Chapter 6, as indicated with the blue arrow connecting the literature review and health modeling study in the figure. The findings from the $PM_{2.5}$ personal exposure monitoring study in Chapters 4 contributed to knowledge regarding US diplomats' $PM_{2.5}$ personal exposure and how diplomats' time activity patterns and microenvironment specific $PM_{2.5}$ concentrations contributed to their $PM_{2.5}$ personal exposure. Results from Chapter 4 were useful in the development of the research plan for the intervention study detailed in Chapter 5 including the information learned about diplomats' indoor home $PM_{2.5}$ concentrations and amount of time diplomats' spent at home. Knowledge gained through the $PM_{2.5}$ personal monitoring studies was considered when developing the health model, with the connection indicated by the blue arrow line connecting these items on Figure 5. Results from Chapter 5, specifically the impact of mitigation used at home on $PM_{2.5}$ personal exposure, were applied to the health model in Chapter 6 to estimate how diplomats' life expectancy calculations may change when diplomats' use a high level of mitigation in their home when they live in cities with high ambient $PM_{2.5}$. The direct use of results from Chapter 5 on the health model in Chapter 6 is indicated by the black arrow line connecting these items on Figure 5. The health model yielded estimates of the impact of $PM_{2.5}$ exposure on the life expectancy for US diplomats and their accompanying family members, including $PM_{2.5}$ exposure acquired while serving as a diplomat (or accompanying a parent who is a diplomat) in multiple international locations with a variety of ambient $PM_{2.5}$ levels.

1.4 Impact of the COVID-19 Pandemic on My Research

My original plan of research presented during my Upgrade seminar on 11 September 2019 included a full year of $PM_{2.5}$ personal monitoring among US diplomats and family members living in Kathmandu, Nepal and in Pristina, Kosovo (Edwards L., 2019). The study in Kathmandu began on 15 September 2019 and was halted on 20 March 2020 due to the COVID-19 pandemic and related changes in US diplomats' activities in Kathmandu. Eighteen of the 30 study participants in Kathmandu relocated back to the US in late March 2020 and nearly all of the remaining participants began working from their residences in Kathmandu due to the stay at home orders by the government of Nepal. Four of the remaining study participants in Kathmandu continued to participate in short-term $PM_{2.5}$ personal monitoring and a natural experiment study was developed. The four diplomats' $PM_{2.5}$ exposure and time in various microenvironments prior to the COVID lockdown period (September 2019 to February 2020) were compared to those during the COVID lockdown (March to June 2020). Results of the natural experiment are included in Chapter 4 of my thesis. The large scale personal monitoring study in Kathmandu was shifted to an intervention study when I discovered that the US Embassy in Kathmandu began providing new, high capacity air purifiers to US diplomats for use in their homes in late 2019. I utilized the transition period of enhancing mitigation measures as the basis for this intervention study. A majority of the 30 study participants enrolled in the study had received the new, high capacity air purifiers and had completed a $PM_{2.5}$ personal monitoring session before and after the new air purifiers were implemented in their residence in Kathmandu. Results of this study are included in Chapter 5 of my thesis.

In my original plans for my doctoral research presented at my Upgrade seminar, I planned to conduct a $PM_{2.5}$ personal monitoring study in Pristina. The study was planned to begin in May 2020, however, many diplomats who had enrolled in the study were evacuated to the United States in March 2020. Due to competing priorities at the US Embassy, including increasing political instability in Kosovo and shifting priorities to focus on public health considerations for COVID management, the US Embassy in Kosovo withdrew their consideration to host the study (Krasniqi, 2020; Sane et al., 2023).

2 Aim and objectives of the thesis

The aim of this doctoral research is to quantify the impacts of lifetime $PM_{2.5}$ exposure on mortality for US government diplomats and accompanying family members who have multiple international relocations including in cities with high ambient $PM_{2.5}$, in comparison to Americans living exclusively in the US.

The hypothesis of my doctoral research is that US diplomats' $PM_{2.5}$ personal exposure may be considerably lower than ambient $PM_{2.5}$ levels in highly polluted cities and, when high capacity air purifiers are used in diplomats' residences, diplomats' $PM_{2.5}$ related mortality may be similar to that of Americans living exclusively in the US.

2.1 Objectives

2.1.1 Objective one

Research question:

- Does relocation between the areas with different average air pollution concentrations contribute to the change in morbidity or mortality?

Objective 1

- Synthesize the current evidence of the impacts of air pollution on mortality and morbidity among populations who relocate between the areas with different ambient air pollution concentrations.

Specific sub-objectives:

1a. Investigate the health outcomes, pollutants, time frame of measurable health impacts and the observed magnitude of the reported associations.

1b. Identify the major study designs and challenges to quantify the health impacts due to changes in ambient air pollution level in relation to relocations.

2.1.2 Objective two

Research questions:

- How do US diplomats' activity patterns in various microenvironments contribute to their personal $PM_{2.5}$ exposure level in a city with high ambient $PM_{2.5}$?
- How does the use of air purifiers in US diplomats' homes in a city with high ambient $PM_{2.5}$ contribute to reduce the $PM_{2.5}$ personal exposure level for US diplomats and their accompanying family members?

Objective 2:

- Conduct repeated personal $PM_{2.5}$ exposure monitoring sessions for 48 hours to characterize individual exposure profiles for US diplomats and family members living in a city with high ambient $PM_{2.5}$ pollution.

Specific sub-objectives:

2a. Quantify the $PM_{2.5}$ exposure level for US diplomats and family members, who live in a city with high ambient $PM_{2.5}$, at the individual level by microenvironment and examine the relationship between the cumulative $PM_{2.5}$ personal exposure and time spent in each microenvironment utilizing a natural experiment opportunity due to the COVID-19 pandemic (before vs during pandemic comparison).

2b. Investigate whether the relationship between $PM_{2.5}$ personal exposure and ambient $PM_{2.5}$ changed after implementing enhanced mitigation measures at home (i.e. additional air purifiers and improvement of home air tightness) compared to that before implementation in the form of intervention study.

2.2.3 Objective three

Research question:

- **Is mortality risk associated with lifetime $PM_{2.5}$ exposure higher among US diplomats and family members with multiple international relocations including highly polluted cities compared to Americans living exclusively in the US?**

Objective 3:

- Develop a health impact model to quantify the mortality burden associated with $PM_{2.5}$ exposure among a population who relocate to different cities over the world and apply the model to the US diplomats and family members with multiple international assignments including highly polluted cities.

Specific sub-objectives:

3a. Quantify the health burden, in terms of mortality and life years lost, associated with $PM_{2.5}$ exposure for US diplomats and family members based on a set of 20-year career overseas assignment profiles.

3b. Quantify the degree to which the indoor $PM_{2.5}$ mitigation measures currently in use in highly polluted cities (i.e. the use of air purifiers and improving home air tightness) can mitigate the $PM_{2.5}$-related health burden.

2.2 Overall PhD structure

Table 1. Overall PhD structure

Objectives	**Methods/ Study Design**	**Input for Other Objectives**	**Chapter and Paper**
1. Synthesize the current evidence of the impacts of air pollution on mortality and morbidity among populations who relocate between the areas with different ambient air pollution concentrations. 1a. Investigate the target health outcomes, pollutants, time frame of measurable health impacts and the observed magnitude of the reported associations. 1b. Identify the major study designs and challenges to quantify the health impacts due to changes in ambient air pollution level in relation to relocations.	Literature review	• Identification of the reported health outcomes, pollutants, and time frame of the impact to be considered for inclusion in Objective 3. • Identified major study designs and challenges in quantification inform the method for Objective 3.	**Chapter 3** Paper: "Health effects in people relocating between environments of differing ambient air pollution concentrations: A literature review"
2. Conduct repeated personal $PM_{2.5}$ exposure monitoring sessions for 48 hours to characterize individual exposure	Natural experiment study		

profiles for US diplomats and family members living in a selected city with high ambient $PM_{2.5}$.			
2a. Quantify the $PM_{2.5}$ exposure level for US diplomats and family members, who live in a city with high ambient $PM_{2.5}$, at the individual level by microenvironment and examine the relationship between the cumulative $PM_{2.5}$ personal exposure and time spent in each microenvironment utilizing a natural experiment opportunity due to the COVID-19 pandemic (before vs during pandemic comparison).	Natural experiment study (before vs during COVID-19 pandemic comparison)	• Supporting evidence for diplomats' exposure patterns in the sensitivity analysis of Objective 3.	**Chapter 4** Paper: "Personal exposure monitoring of $PM_{2.5}$ among US diplomats in Kathmandu during the COVID-19 lockdown, March to June 2020"
2b. Investigate whether the relationship between $PM_{2.5}$ personal exposure and ambient $PM_{2.5}$ changed after implementing enhanced mitigation measures at home (i.e. additional air purifiers and improvement of home air tightness) compared to that before implementation in the form of intervention study.	Intervention study, meta-regression of the slope of indoor/ambient $PM_{2.5}$ ratio, comparison of	• Effectiveness of the enhanced mitigation measures was applied in Objective 3.	**Chapter 5** Paper: "Impact of mitigation measures to improve home indoor air quality in Kathmandu, Nepal"

	before vs after intervention		
3. Develop a health impact model to quantify the mortality burden associated with $PM_{2.5}$ exposure among a population who relocate to different cities over the world and apply the model to the US diplomats and family members with multiple international assignments including highly polluted cities. 3a. Quantify the health burden, in terms of mortality and life years lost, associated with $PM_{2.5}$ exposure for US diplomats and family members based on a set of 20-year career oversea assignment profiles. 3b. Quantify the degree to which the measures currently in use in highly polluted cities can mitigate the $PM_{2.5}$-related health burden.	Health modeling with life table method using inception and cessation lags		**Chapter 6** Paper: "Health impacts of exposure to $PM_{2.5}$ for diplomats with multiple international relocations: modeling study"

2.3 Summary

The overall structure of the PhD is included in Table 1, with information added regarding the study design and use of results from each activity included in the thesis. Objective 1 is addressed in the literature review paper (Chapter 3). Objective 2 is included in natural experiment publication (Chapter 4) and intervention study publication (Chapter 5). The health modeling study is described in the manuscript (Chapter 6).

PART II: Results

3 $PM_{2.5}$ related health impacts among populations who relocated to an area with a change in ambient $PM_{2.5}$: Literature review

3.1 Introduction

This chapter synthesizes the current evidence, through a literature review, of the health impacts of air pollution among populations who have relocated between the areas with different ambient average air pollution concentrations. Relocations between environments of different ambient air pollution level serve as an opportunity of natural experiment to examine how health status, including mortality, may change after an abrupt change in the exposure to certain air pollutants. This literature review included any human epidemiological studies with at least one relocation without any time limit for the duration of the relocation. In order to collect wider knowledge of the evidence, the review did not exclude any specific age groups or geographic regions. Target air pollutants were specified as $PM_{2.5}$, PM_{10}, O_3, SO_2 and NO_2 based on the current knowledge of observed health impacts of these pollutants. The comparator group depends on the study design, i.e. within-person before and after relocation, between-persons/groups among the movers with different magnitude of changes in exposure level, or comparisons of movers to non-movers. A wide range of health outcomes were selected in relation to a change in ambient exposure, including mortality, birth outcomes (low birth weight, pre-term birth and small for gestational age), respiratory symptoms and hospitalizations, lung function, cardiovascular status metrics (blood pressure, heart rate, heart rate variability), and serological biomarkers of inflammation (IL-6, G-CSF) and cardiovascular function (12-HETE, CRP, fibrinogen).

This chapter addresses the research objective (1) synthesize the current evidence of the impacts of air pollution on mortality and morbidity among populations who relocate between the areas with different average air pollution concentrations and sub-objectives (1a) investigate the health outcomes, pollutants, time frame of measurable health impacts and the observed magnitude of the reported associations, and (1b) identify the major study designs and challenges to quantify the health impacts due to changes in average of air pollution exposure level in relation to relocations.

This activity included in Chapter 3 was accepted for publication in the journal *Environmental Pollution* in October 2021. The supplementary material from this paper is included in Appendix 1.

3.2 Research Paper

The LSHTM Research Paper Cover Sheet and published research paper for this activity are included on subsequent pages. The published research paper has been transformed from an Adobe document to MS Word to optimize viewing in my thesis. The published research paper is also available on the webpage https://www.sciencedirect.com/science/article/pii/S0269749121018960 .

3.2.1 Research Paper Cover Sheet

LONDON
SCHOOL of
HYGIENE
&TROPICAL
MEDICINE

London School of Hygiene & Tropical Medicine
Keppel Street, London WC1E 7HT

T: +44 (0)20 7299 4646
F: +44 (0)20 7299 4656
www.lshtm.ac.uk

RESEARCH PAPER COVER SHEET

Please note that a cover sheet must be completed for each research paper included within a thesis.

SECTION A – Student Details

Student ID Number	lsh1514008	**Title**	Ms.
First Name(s)	Leslie		
Surname/Family Name	Edwards		
Thesis Title	$PM_{2.5}$ Exposure and Associated Health Impacts on United States Government Diplomats and Accompanying Family Members With Multiple International Relocations: Exposure Measurement and Health Modeling Study		
Primary Supervisor	Dr. Ai Milojevic		

If the Research Paper has previously been published please complete Section B, if not please move to Section C.

SECTION B – Paper already published

Where was the work published?	Environmental Pollution		
When was the work published?	12 October 2021		
If the work was published prior to registration for your research degree, give a brief rationale for its inclusion	Not Applicable		
Have you retained the copyright for the work?*	**No**	Was the work subject to academic peer review?	**Yes**

*If yes, please attach evidence of retention. If no, or if the work is being included in its published format, please attach evidence of permission from the copyright holder (publisher or other author) to include this work.

SECTION C – Prepared for publication, but not yet published

Where is the work intended to be published?	
Please list the paper’s authors in the intended authorship order:	
Stage of publication	Choose an item.

SECTION D – Multi-authored work

For multi-authored work, give full details of your role in the research included in the paper and in the preparation of the paper. (Attach a further sheet if necessary)	My role and independent contributions to this research included planning, conducting, and leading the literature review and developing the manuscript from the original draft to the accepted version of this paper. Specifically, I implemented the search criteria, agreed upon among PhD supervisors Dr. Ai Milojevic (AM) and Dr. Paul Wilkinson (PW), and collaborator Dr. Gemma Rutter (GR) and myself, and conducted the literature searches in Medline, Global Health and Embase databases. I imported all abstracts and published articles into the Covidence software that was used in the review process. I read all the abstracts and research articles included in the review to analyze and extract the necessary information with one of co-reviewers (AM, PW, and GR) as a pair. I maintained the database of the 15 reviewed papers including study designs, results, limitations, and risk of bias in order to track input from all co-reviewers. I wrote the first draft of the manuscript including tables and figures and developed to the final version of this paper by incorporating advice from co-authors. I also led the submission process of this paper and correspondence with the journal editor and its external reviewers. Overall, I led this paper from the initial formation of the idea to the publication, as the first author. AM and PW contributed as co-reviewers by extracting key literature information and risk of bias information. AM, PW, and GR reviewed the draft of this paper and provided comments to support the development of this article, for which I am grateful.

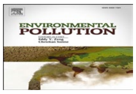
SECTION E

Student Signature	Leslie Edwards
Date	18 January 2024

Supervisor Signature	Ai Milojevic
Date	18 January 2024

Environmental Pollution 292 (2022) 118314

Environmental Pollution
journal



Health effects in people relocating between environments of differing ambient air pollution concentra literature review

Leslie Edwards [a,*], Paul Wilkinson [a], Gemma Rutter [b], Ai Milojevic [a]

[a] *London School of Hygiene and Tropical Medicine, London, England, United Kingdom* [b] *United States Embassy in Kathmandu, Nepal*

ARTICLE INFO

Keywords:
Air pollution
Particulate matter
Migration
Relocation
Lung function
Mortality

ABSTRACT

People who relocate to a new environment may experience health effects from a change in ambient air pollution. We undertook a literature review of studies of such relocations and health effects and report the results as a narrative analysis. Fifteen articles of heterogeneous designs met the inclusion criteria. Four short-term (relocation duration less than six months) and three long-term (relocation duration six months or greater) studies reported evidence of the effect of relocation on physiological outcome, biomarkers, or symptoms. All had potential weaknesses of design or analysis but, as a whole, their results are broadly consistent in suggesting short-term adverse effects of air pollutants or their reversibility. One long-term study provided evidence that changes in air pollution exposure during adolescence have a measurable effect on lung function growth. Four cohort studies were also identified that used relocation to strengthen evidence of air-pollution-exposure relationships by using a design that incorporates effective randomization of exposure or the use of relocation to improve exposure classification. However, three studies of relocation during pregnancy provided limited evidence to conclude an effect of relocation-related change in exposure on pregnancy outcome. Overall, most relocation studies are consistent with short- or long-term adverse effects of air pollution on biological function or mortality, but many studies of change in exposure have design weaknesses that limit the robustness of interpretation. We outline principles for improved design and analysis to help strengthen future studies for the insights they can provide from their quasi-experimental designs, including on the nature and timing of functional changes of relocation- related changes in exposure to ambient air pollution.

Introduction

The Global Burden of Diseases, Injuries, and Risk Factors Study 2015 estimates that 4.2 million deaths (95% confidence interval (CI): 3.7–4.8 million), or roughly 1 in 3 deaths globally, were due to exposure to fine particulate matter smaller than 2.5 μm ($PM_{2.5}$) (Cohen et al., 2017). The most common causes of death attributable to air pollution include stroke, ischemic heart disease, lung cancer, and chronic obstructive pulmonary disease (Cohen et al., 2017; C. Liu et al., 2019). Long term exposure to $PM_{2.5}$ increases the relative risk of all-cause mortality by 8% and acute cardiovascular events by as much as 10% (Pope et al., 2020; Rajagopalan et al., 2018). Long-term exposure to nitrogen dioxide (NO_2) has been associated with an increase in mortality due to respiratory, COPD and all-cause mortality (Huangfu & Atkinson, 2020).

The United Nations estimates that nearly 272 million people do not live in the country where they were born (United Nations, 2020). While an extensive body of research is available on both short- and long-term air pollution exposures, most studies have been based on people in an unchanging location with therefore relatively static long-term concentration of ambient air pollution level, except for natural experimental studies where the environment changed due to policy interventions or other events. Less is known about how the health of people who relocate from one area to another with a higher or lower ambient air pollution level.

There are a variety of reasons to relocate including to change jobs, attend university, or to live in a safer environment with better access to food, water, or other resources (Castelli, 2018). People who are required to move for their job including the military and diplomatic corps members are required to complete health and fitness screening prior to the move (Cummings, 2015; United States Department of State, 2020). Though these movers are generally healthier than non-movers,

---

* Corresponding author.
E-mail address: Leslie.Edwards@lshtm.ac.uk (L. Edwards).

Received 25 June 2021; Received in revised form 11 September 2021; Accepted 6 October 2021 Available online 12 October 2021
0269-7491/Published by Elsevier Ltd.

https://doi.org/10.1016/j.envpol.2021.118314

it is unclear how and whether the changes in exposure level to air pollution might influence on their health in long- and/or short term. Military, diplomats, and others may have a 20-year career of moves between areas of high and low air pollution. This information can better inform decisions about relocating (who, when and where) for both employees and employers and also for employers to structure their work assignments of the groups that frequently change their location of work. This review aims to synthesize the current evidence describing the health effects of air pollution among people who have relocated and to identify research gaps in the literature.

Materials and methods

Protocol

The protocol for this study was developed in accordance with the Preferred Reporting Items for Systematic Review and Meta-analysis Protocols (PRISMA-P) standards (Moher et al., 2009). The protocol is registered with the Open Science Foundation (https://osf.io/sh9pg).

Eligibility criteria

The Population, Exposure, Comparator, Outcome, Study Design (PECOS) items were used to develop the study eligibility criteria and are listed in Table 1. The populations studied include humans with exposure to ambient air pollution with at least one relocation during the study period regardless of the length of relocation time period. There was no restriction in the study population based on age, sex, or geographic location. Studies reporting the health effects of exposure to ambient $PM_{2.5}$, PM_{10}, ozone (O_3), sulphur dioxide (SO_2), sulphate constituent particles (SO_4) and/or NO_2 as well as proximity to roads were included. The comparator in each study was the change in ambient air pollution exposure and health metrics using various types of comparisons including within- and between-person comparisons among movers, and comparison of movers to non-movers among the entire study population. Health outcomes studied include lung function metrics (see Table 1), respiratory symptoms and hospitalizations, cardiovascular status metrics including blood pressure, pulse pressure, heart rate (HR), heart rate variability (HRV), serological biomarkers of inflammation, birth outcomes including low birth weight (LBW), preterm birth (PTB), small for gestational age (SGA), and mortality.

Epidemiologic studies with at least one relocation were included in the review. In this study, relocation was defined as movement to a new location for at least 5 days which could occur during a vacation, business trip, deployment, temporary move, or permanent move to a new location. Peer reviewed journal articles and reports issued by governments were included. Articles written in the English language or translated into English from 1989 to 2020 were included in the review. Animal studies, human case reports, review articles and editorials were excluded from this review. Natural experiment studies that the air quality at the same location changes due to some major events or policy interventions instead of the relocation of the study participants, were excluded from the current review as many have previously been discussed and collectively reviewed (Burns et al., 2020; Rich, 2017).

Information sources

Published literature was searched to identify articles that matched the PECOS eligibility criteria as defined above. Medline, Global Health and Embase were searched from January 1989 to October 2020 to identify English language publications using a search strategy consisting of three categories of search terms joined by logical AND connections: (1) air pollution AND (2) relocation, change or migration AND (3) health condition or mortality (Appendix A). The search strategy was developed in consultation with a librarian at the US Centers for Disease Control and Prevention and London School of Hygiene and Tropical Medicine. We reviewed the references of included articles for air pollution epidemiological studies that would be appropriate for this review article.

Table 1 Inclusion and Exclusion Criteria for each PECOS domain regarding the health effects of air pollution exposure among people who relocate.

PECOS	Inclusion	Exclusion
Population	• Human population of all ages in developed and developing countries. No geographic restrictions. • Study population exposed to ambient air pollutants.	• Animal studies or laboratory-based *in vitro* studies
Exposure	• Exposure to ambient $PM_{2.5}$, PM_{10}, O_3, SO_2 and/or NO_2 • Proximity to roads	
Comparator	• Change in exposure to ambient air pollution using comparisons within-person, between-person among the movers or comparisons of movers to non-movers group.	• None
Outcome	• Health outcomes selected in relation to a change in ambient exposure include: o lung function metrics (FEV1, FER, FEF25-75, FeNO, FVC, MMEF, MVV, PEFR) o respiratory symptoms and hospitalizations o cardiovascular status metrics (blood pressure, HR, HRV) o serological biomarkers of inflammation (IL-6, G-CSF)) and cardiovascular function (12-HETE, CRP, fibrinogen) o birth outcomes (LBW, PTB, SGA) o mortality	• Health status assessed and reported only after the relocation and not before the relocation
Study	• Human epidemiologic studies with at least one relocation.	• Publications including review articles, opinion articles, editorials, newspaper articles • Natural experiment studies describing the health effects following interventions or events

Abbreviations: 12-HETE (12 hydroxyeicosatetraenoic acids), CRP (C-reactive protein), FEV_1 (forced expiratory volume in 1 s), ER (forced expiratory flow rate), FEF_{25-75} (forced expiratory flow rate between 25% and 75% of forced vital capacity), FeNO (fractional exhaled nitric oxide), FVC (forced vital capacity), G- CSF (granulocyte colony-stimulating factor), HR (heart rate), HRV (heart rate variability), IL-6 (interleukin-6), MMEF (maximal mid-expiratory flow), MVV (maximum voluntary ventilation), PEFR (peak expiratory flow rate), HR (heart rate), HRV (heart rate variability), LBW (low birth weight), PTB (preterm birth), SGA (small for gestational age).

Study selection

References were managed using Covidence software (www.covidence.org). Duplicate references were identified and deleted. Abstracts of remaining articles were screened by two independent investigators (L. E., A.M., G.R., and/or P.W.) to identify findings that were relevant to the current review and compared against the PECOS criteria. Discordant selections were discussed among the team either moved forward for the full paper review or deemed irrelevant to this research.

Data collection

Data from the included studies were independently extracted by two investigators. Variables extracted include study location(s), time period, participant demographics, number of study subjects, pollutant types reported, duration and timing of exposures (relocations), exposure measurements, health outcomes including when they were measured, covariates included in the analysis and limitations of the study.

Risk of bias evaluation

Articles were reviewed for data quality and bias by two independent reviewers using a tool developed by the authors, based on the Navigation Guide (Fig. 1) (Johnson et al., 2016). Articles were assessed for nine factors including the recruitment strategy, blinding of participants, robustness of exposure assessment, robustness of outcome assessment, confounding, completeness of outcome reporting, selective outcome reporting, conflicts of interest and other biases. Four rating levels were applied for each factor in the risk of bias, namely 'low', 'probably low', 'probably high' and 'high'. An overall risk of bias rating was designated for each study and was based on the highest risk of bias rating for any of the nine factors evaluated. Conflicts in bias assessments were discussed by the reviewers and reviewers ultimately came to agreement about the assessment grading. *2.7.*

Reporting of relocation results

Various forms of epidemiological analysis were reported in the original studies but our focus in this review was on the specific effect of the relocation. For studies of physiological outcome, we therefore present (in Table 3) the binary comparison of the health outcomes measured at the original location and at the new location (or during phases of travel/relocation where appropriate). We indicate the general difference in pollutants at the original and new locations but do not attempt to translate the effect of relocation into a difference in health outcome for a unit difference in pollutant. An exception to this is the study by Avol et al. (2001) which reported the change in annual lung function growth rates in relation to relocation changes in PM_{10}, NO_2, or O_3. In the case of the three studies of pregnancy outcome, the principal focus of the original studies was on the pregnancy outcome air pollution association in movers *vs* non-movers rather than on the effect of relocation itself; none reported the effect of relocation in relation to change in pollution. Similarly, for the included long-term cohort studies, the reported outcomes were air pollution-mortality or air pollution-hospital admission associations rather than the relative risk of relocation.

Results

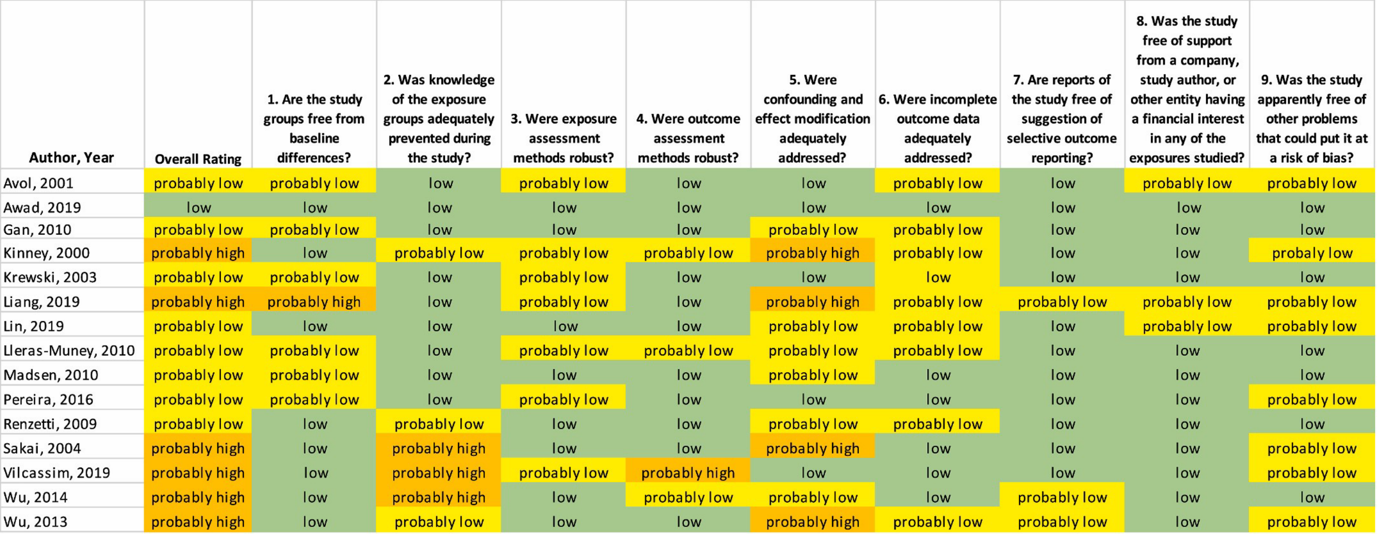
Search results and study characteristics

The literature search identified 4935 abstracts and 262 duplicates were removed prior to screening (Fig. 2). Reviewers examined 122 articles and determined that 15 articles met the PECOS criteria and were selected for inclusion. Selected references included four articles with a short-term relocation less than six months in duration and 11 articles with a long-term relocation of six months or greater. Study types include eight panel studies and seven cohort studies. (Table 2). Twelve articles included relocations within the same country and three included international relocations. Two articles included relocations mainly from low to high ambient air pollution, four articles included relocations mainly from high to low and the remaining nine articles included relocations from both low to high and high to low ambient air pollution. The summary of relocations, timing of the follow-up measurements, findings and bias ratings were described in Table 3. The overall risk of bias was 'probably high' for seven studies (including three of four studies investigating relatively short-term effects of relocation change in exposures), 'probably low' for seven studies and 'low' for one study (Fig. 2). Due to the heterogeneity of study populations and pollutants, no meta-analysis was performed.

Short-term relocations and health effects

Four panel studies were of the health effects of short-term (less than 6 months) travel or posting to more/less polluted environments: three were analyzed as uncontrolled, within-person changes in lung function, cardiovascular function or biomarkers of cardiovascular function and inflammation and one was a between-person comparison of lung function in relation to ambient O_3.

Vilcassim *et al.* investigated 34 non-smoking young adult travelers from New York to destinations around the world and found evidence of reduced lung function including FEV_1, and peak expiratory flow rate (PEFR), reduced heart rate variability and increased respiratory symptoms within a week of arrival in the higher $PM_{2.5}$ destination city (Vilcassim et al., 2019). All analyses were of within-person (before-after) change without other control. The risk of bias rating for this study was 'probably high' because of self-reporting/measurement of health outcome data. Mean [± standard deviation (SD)] $PM_{2.5}$ increased six-fold during the study, from 8.7 ± SD 4.7 $\mu g/m^3$ in New York City to 62.1 ± 79.1 $\mu g/m^3$ in destination locations. An increase of 10 $\mu g/m^3$



Author, Year	Overall Rating	1. Are the study groups free from baseline differences?	2. Was knowledge of the exposure groups adequately prevented during the study?	3. Were exposure assessment methods robust?	4. Were outcome assessment methods robust?	5. Were confounding and effect modification adequately addressed?	6. Were incomplete outcome data adequately addressed?	7. Are reports of the study free of suggestion of selective outcome reporting?	8. Was the study free of support from a company, study author, or other entity having a financial interest in any of the exposures studied?	9. Was the study apparently free of other problems that could put it at a risk of bias?
Avol, 2001	probably low	probably low	low	probably low	low	low	probably low	low	probably low	probably low
Awad, 2019	low	low	low	low	low	low	low	low	low	low
Gan, 2010	probably low	probably low	low	low	low	probably low	probably low	low	low	low
Kinney, 2000	probably high	low	probably low	probably low	probably low	probably high	probably low	low	low	probaly low
Krewski, 2003	probably low	probably low	low	probably low	low	low	low	low	low	low
Liang, 2019	probably high	probably high	low	probably low	low	probably high	probably low	probably low	probably low	probably low
Lin, 2019	probably low	low	low	low	low	probably low	probably low	low	probably low	probably low
Lleras-Muney, 2010	probably low	probably low	low	probably low	probably low	probably low	probably low	low	low	low
Madsen, 2010	probably low	probably low	low	low	low	probably low	low	low	low	low
Pereira, 2016	probably low	probably low	low	probably low	low	low	low	low	low	probably low
Renzetti, 2009	probably low	low	probably low	low	low	probably low	probably low	low	low	low
Sakai, 2004	probably high	low	probably high	low	low	probably high	low	low	low	probably low
Vilcassim, 2019	probably high	low	probably high	probably low	probably high	low	low	low	low	probably low
Wu, 2014	probably high	low	probably high	low	probably low	probably low	low	probably low	low	low
Wu, 2013	probably high	low	probably low	low	low	probably high	probably low	probably low	low	probably low

Fig. 1. Data quality and risk of bias assessment results.

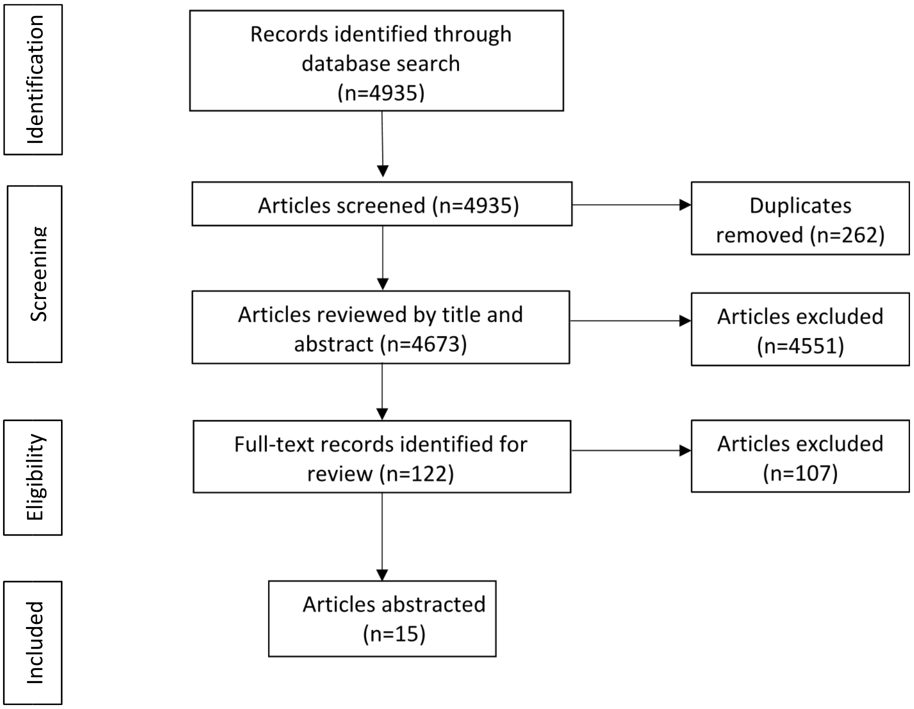


Fig. 2. Flow diagram of search strategy and article selection.

ambient PM$_{2.5}$ was associated with a 7 mL decrease in FEV$_1$. People who travelled to cities with PM$_{2.5}$ higher than New York City had increased upper respiratory symptoms including cough, throat irritation and nasal congestion. Participants were provided with a wrist monitor to assess their BP and they wore equipment that continuously monitored their HRV. Participants performed their own lung function testing and respiratory symptoms were self-reported. Although there was no association between change in ambient PM$_{2.5}$ and BP in the study, a 10 μg/m^3 increase in evening PM$_{2.5}$ was associated with a 0.2 beats/min increase in heart rate, and a change in HRV including 0.6 ms (ms) (95% confidence interval (CI), −1.01, −0.24) change in SD normal-normal interval (SDNN) and − 0.7% (−1.09, −0.25) change in the proportion of normal-normal intervals that exceed 50 ms (PNN50).

A similar study by Lin *et al.* (risk of bias rating 'probably low') measured biomarkers in 26 Los Angeles (LA), USA, university students, who spent 10 weeks in summer studying in Beijing (Lin et al., 2019). Blood and urine samples were taken before travel, 6–8 weeks after arriving in Beijing, and 4–7 weeks after return to LA. Levels of urinary polyaromatic hydrocarbon (PAH) were 176% higher after 6–8 weeks in Beijing compared to their pre-travel level in LA and the lipid peroxidation biomarker 12-hydroxyeicosatetraenoic acid (12-HETE) increased by 998% (statistically significant finding with false discover rate <5% after Benjamini-Hochberg adjustment) while in Beijing and decreased by 79% (comparing LA-after to Beijing sampling) after return to LA. C-reactive protein (CRP) increased by 101% while in Beijing and decreased by 53% after return to LA and fibrinogen increased by 48% while in Beijing and decreased by 37% after return to LA. Changes for most biomarkers studied reversed when participants returned to LA although several biomarkers remained elevated compared to pre-travel (baseline) levels initially measured in LA.

Renzetti *et al.* (risk of bias rating 'probably high') studied 37 children with mild asthma and allergies from highly polluted urban environments before and after joining a one week summer camp in Ovindoli, Italy, a low-traffic rural area 1500 m above sea level (Renzetti et al., 2009). All measured pollutants were substantially lower at the camp compared with the urban locations: e.g. mean PM$_{10}$ was lower by 76%

(56.9 ± SD 13.1 μg/m^3 *vs* 13.8 ± 5.6 μg/m^3), O_3 by 52% (137.3 ± 15.3 *vs* 66.2 ± 3.9 ppb) and NO_2 by 93% (97.4 ± 11.8 μg/m^3 *vs* 6.6 ± 0.5 μg/m^3). The relocation was accompanied by changes in biomarkers of upper and lower airway inflammation, an average fourfold decrease in nasal eosinophils ($p < 0.002$) and reduced eosinophilic inflammation of the lower airways, reflected by a significant decrease in mean FeNO concentration ($p < 0.028$), mainly due to reduction in those with previously high urban concentrations. Participants' PEFR increased by an average of approximately 80 L/min after the relocation ($p < 0.0001$).

Kinney and Lippman (risk of bias rating 'probably high') studied 72 military college students in West Point, New York, USA that spent the summer working outdoors for an average of 11 hours a day in one of four US locations in 1990 for their Drill Cadet Leadership Training (DCLT) (Kinney & Lippmann, 2000). The main comparison was of the 21 cadets who attended DCLT in Fort Dix with the 51 posted to any one of the other three locations: Fort Dix had appreciably higher concentrations of O_3, higher levels of sulphur dioxide (SO_2) and moderately higher levels of PM_{10} than the other locations. Those who attended Fort Dix had an appreciably greater reduction in FEV_1 than those who attended one of the other three camps (change in FEV_1 of − 0.078 (standard error (SE) 0.041) *vs* − 0.031 (SE 0.024) liters; change in FEF_{25-75} of −0.173 (SE 0.104) *vs* 0.075 (SE 0.076) liters/second). However, forced vital capacity increased at all locations to a statistically non-significant degree. Although there was some evidence for an increase in selected respiratory symptoms during the DCLT assignment, no clear evidence was presented of a difference between Fort Dix and other locations.

Long-term relocations and health effects

Eleven relocation studies included cohorts of varying size with long- term relocations of 6 months or longer. Health outcomes studied include annual lung function growth rates, lung function, blood pressure, biomarkers of inflammation, respiratory-related hospitalizations, pregnancy outcome and mortality.

Lung function, blood pressure and inflammatory biomarkers

Avol *et al.* (risk of bias assessment 'probably low') undertook a study of 110 children enrolled in the California Children's Health Study at age 10 or 11 years who moved to a new location by age 15 years (Avol et al., 2001). The mean change in ambient PM_{10} for children who relocated ranged from − 32.9 µg/m^3 to 13.4 µg/m^3 (Huangfu & Atkinson, 2020). Analyses suggested that increasing exposure to PM_{10} was associated with changes in long-term health effects including lower annual growth in maximal mid-expiratory flow (MMEF) by 16.6 ml/s ($p < 0.04$), PEFR by 34.9 ml/s ($p < 0.007$) and FEV_1 by 6.6 ml ($p < 0.06$). When children moved to areas with higher NO2 and O3 levels, a decrease in annual lung growth rates was observed, but these results were not statistically significant at the 5% level. A stronger trend was noted among children who migrated at least three years before follow-up than for those who moved in the prior one to two years.

Table 2

Characteristics of studies included in the review (n = 15).

Author (Year)	Design	Study population, follow-up period (time)	Setting	Exposure	Health Outcomes	Main analysis (what/ when measured, analyzed)	Limitations
Short term relocations of less than 6 months (n = 4)							
Vilcassim et al. (2019)	Panel study	34 healthy non- smoking adults (mostly university students) who travelled internationally for 1+ week in 2018	NY (US) to Europe, South/ East Asia and Africa	$PM_{2.5}$ (fixed monitoring)	FEV_1, PEFR, BP, HR, HRV, respiratory symptoms	Exposure and health outcomes were measured twice a day (morning and evening) for 3 weeks. Change in repeated measures of exposure and outcomes were analyzed in mixed- effect model.	Small study, self- administered lung function test, $PM_{2.5}$ measured by different system (US embassy or local), no non- movers control.
Lin et al. (2019)	Panel study	26 healthy non- smoking students (aged 18–30 yrs) in California who travelled to Beijing for 10 weeks in summer 2014 or 2015.	LA (US) to Beijing (China)	Urinary PAH metabolite levels	Serum biomarkers of lipid peroxidation and inflammation	Exposure and health outcomes were measured 3 times during the study (10–15 weeks of follow-up). Changes in repeated measures of outcomes were analyzed in mixed- effect model.	Small study, multiple tests for range of combination of biomarkers and urinary OH-PAH, no non- movers control.
Renzetti et al. (2009)	Panel study	37 untreated allergic children (aged 7–17 yrs) with mild persistent asthma in Italian urban city who joined school camp in rural area for 1 week in summer 2006.	Pescara to Ovindoli (Italy)	PM_{10}, O_3, NO_2, CO, Benzene, pollen (fixed monitoring)	PEFR, FeNO	Air quality and health outcomes were measured 6 times for 1 week follow- up: morning, mid-day, and evening on Day 1 and 7. Difference in exposure and clinical measurements were compared by Student's t-test.	Limited statistical analysis, other meteorological changes not considered, children with mild persistent asthma only, no non- movers control.
Kinney and Lippmann (00)	Panel study (comparison between person)	72 US military cadets aged 18–22 years who conducted outdoor training for 5 weeks (11 Jul to 15 Aug 1990) at 4 locations.	NY to Fort Dix (higher O_3), Fort Benning, Fort Leonard Wood and Fort Sill (US)	O3, PM10, SO2 (fixed monitoring, grouped into high/moderate)	FEV_1, FVC, FEF_{25-}75, respiratory symptoms	Health outcomes and O_3 exposure were measured daily during study period. Changes in mean lung functions across the two levels of O_3 exposure were examined by *t*-test. Multiple linear regression model was applied to adjust for other influential factors.	Small study, no on-site exposure measurement, before vs after comparison only, possible combined effects with other particles from dust and/ or passive smoking.
Long-term relocations of at least 6 months (n=11)							
Avol et al. (2001)	Panel study (comparison	110 children aged 10–11 years in between 1993–1994 who person) relocated from Sothern California to another US location for 1+ years (subset of Children's Health Study).	California to other cities in California, Arizona, Nevada, Oregon, Washington or Utah (US)	PM_{10}, NO_2, and O_3 (community monitoring in 1994, 1998 and change)	FEV_1, FVC, MMEF, PEFR, respiratory symptoms	Lung functions were examined at study entry 1993/94 and Jan/Jun 1998. Annual average changes in lung functions (age adjusted) were regressed linearly to average change in air pollution, with adjustment for sex, race, entry year, change in height/ weight/BMI and interaction between sex and change in height.	Small study, children only, narrow PM exposure range, no non- movers control.

Table 2

Author (Year)	Design	Study population, follow-up period (time)	Setting	Exposure	Health Outcomes	Main analysis (what/ when measured, analyzed)	Limitations
Wu et al. (2013)	Panel study	39 Chinese healthy male university students who studied in suburban campus for the first 2 years (Sep 2008 to Jul 2010) and relocated to the urban campus for the next 2 years (Aug 2010 to Jul 2012) (HVNR cohort).	Liangxiang (suburban) to Beijing (urban) (China)	$PM_{2.5}$ and constituents (fixed monitoring at campus), PM_{10} (city monitoring <5 km)	BP, PP	Health outcomes were measured during 12 biweekly visits (4 visits in each of the 3 periods of the study). Paired *t*-test to compare mean BP changes between periods by subject, and mixed effects regression models to estimate associations between exposure and BP.	Small study, $PM_{2.5}$ measured at fixed sites, possible confounding due to season, location and sources, other gaseous pollutants not measured, possible impacts of stress due to progression of education, no non- movers control.
Wu et al. (2014)	Panel study	21 Chinese healthy male university students in HVNR cohort (subset of Wu et al., 2013).	Liangxiang (suburban) to Beijing (urban) (China)	$PM_{2.5}$ and Temperature (fixed monitoring)	FEV_1, PEFR, respiratory symptoms	Health outcomes were measured twice daily (morning and evening) for three time periods. Main effect of $PM_{2.5}$ and temperature were examined with lagged effects 1hr-7d, as well as effect modification. Repeated measures were analyzed in mixed-effect model.	Small study, lung function self-measured, possible confounding by seasonal and location-related changes, no non-movers control.
Sakai et al. (2004)	Panel study	39 male workers on a ship who travelled from Japan to Antarctica for 1 year in early 1999.	Kyusyu (Japan) to Antarctica	$PM_{0.3-2}$, PM_{2-5}, PM_5 (monitoring site on the ship during voyage, in Kyusyu)	FVC, FEV_1, FER, FEF_{25-75}, PEFR, MVV, leukocyte counts, G-CSF, IL-6	Blood samples and lung function were measured 7 times after the departure. Differences within person were tested by repeated measure ANOVA with Bonferroni-type multiple comparison. Magnitude of PM impacts was examined in regression analysis. Differences between smokers and non- smokers was examined.	Small study, other Antarctic environmental factors (diet changes, temperature, circadian rhythm) were not considered, no non-movers control.
Madsen et al. (2010)	Cohort study (population based), movers vs non-movers	25,229 mother and live singleton birth pairs in Norway including 7163 who moved during pregnancy in 1999–2002	Oslo (Norway)	PM_{10}, $PM_{2.5}$, NO_2 (Dispersion model at 1 × 1km grid, trimester-average)	Term birth weight, LBW, SGA	Birth records were linked to Statistics Norway to extract mother's information (ethnicity, education, work addresses, residential change – address and time). Logistics and general near regression model were used.	Comparison between mover and non-movers only. Associations between exposure and outcomes were not quantified, fundamental difference in characteristics between non-movers and movers.

(*continued on next page*)

Table 2

Author (Year)	Design	Study population, follow-up period (time)	Setting	Exposure	Health Outcomes	Main analysis (what/ when measured, analyzed)	Limitations
Pereira et al. (2016)	Cohort study, movers vs non-movers	9587 singleton pregnant women in Connecticut, US from 4 cohort studies, who were recruited at <25 weeks or <16 weeks of pregnancy in 1988–2008	Connecticut (US)	PM$_{10}$ (fixed monitoring <100 km or IDW, trimester- average)	PTB, LBW, SGA	Women were interviewed 2–4 times in pregnancy. Exposure was measured at addresses at recruitment, follow- up interviews and delivery. Logistic regression models were used for LBW and SGA, and a discreet time-to-event model for PTB.	Limited exposure information in earlier trimesters due to late recruitment, activity patterns were not accounted for in the study.
Liang et al. (2019)	Cohort study (population-based), movers vs non-movers	628,439 singleton vaginal live births in Pearl River Delta region, China in 2015–17. 49% was locally registered residents and 51% was migrants.	7 cities (Guangzhou, Shenzhen, Zhuhai, Dongguan, Foshan, Jiangmen, and Zhongshan) in Pearl River Delta (China)	PM$_{2.5}$, O$_3$, NO$_2$, SO$_2$ (fixed monitoring <10 km, trimester-average)	PTB	Cox proportional hazards model to examine the effects of air pollution exposures (by trimesters) on PTB for local residents and migrants separately (single and 2-pollutants model).	Limited confounding controls (no information on parental socioeconomic status, maternal ethnicity, nutrition, hypertensive disorders of pregnancy, maternal smoking status and exposure to environmental tobacco smoke). Definition of movers and non-movers does not reflect time of relocation. No distinguish between spontaneous and medically indicated PTB.
Award et al. (2019)	Cohort study, before vs after among movers	10,679,150 US adults aged 65+ years who enrolled in Medicare and moved during follow up in 2000–2012.	US	PM$_{2.5}$ (neural network model by meteorology, land use, satellite AOD, surface reflectance, absorbing aerosol)	Deaths (all-causes)	The effect of change in exposure on all-cause mortality was estimated using a Cox proportional hazards model stratified by ZIP Code before moving with inverse probability weighting to account for confounding after moving and follow-up time.	Area-based covariates, limited confounder controls (no smoking history, no medical history except hospitalization), possible exposure misclassification due to billing-purpose zip code information, no non-movers control.
Lleras-Muney (2010)	Cohort study, movers vs non-movers	159,275 children aged ≤5 years of married men enlisted in the US army and stationed in the continental US in 1989–1995	US	PM$_{10}$, O$_3$, CO, NO$_2$, SO$_2$, TSP (Kriging and IDW from monitoring data within 50 miles)	Overnight hospitalizations for all-causes and for respiratory conditions	Hospitalization was regressed to annual average of pollutants with family fixed effect and other confounding controls (age, sex, race, occupation rank, weather, and family). Analyses were stratified by age group (0–1, 2–5 and 0–5) and with moves vs without moves in the last 12 months.	Only hospitalization was studied, effects within 1 year are examined (no lag), short-term exposure impacts were not examined, limited generalizability of results.

(*continued on next page*)

(*continued*)

Table 2

Gan et al. (2010)	Cohort study (population based), movers vs non-movers	450,283 residents in Vancouver aged 45–85 years (in 1994–1998) without CHD at baseline who did or did not move residence for 4 years follow up	Vancouver (Canada)	Residential proximity to traffic (≤150m from a highway, >50m from a major road)	Deaths (CHD)	Bivariable logistic regression analysis (with nonexposed group as the reference) and multivariable logistic regression analysis to adjust for age, sex, neighborhood income and comorbidities (diabetes, COPD, hypertensive heart disease). Analyses were repeated by road type and distance band.	Pollutants not directly analyzed, limited confounder control (no smoking, BMI, SES), time after move is not considered, no separation from noise impacts.
Rawski et al. (2003)	Cohort study (reanalysis), movers vs non-movers	8111 white adults aged 25–74 years in the US enrolled in the Harvard Six Cities Study in 1975 (16 years follow up). 18.5% moved from their original city of residence.	Harriman, Portage, Steubenville, St. Louise, Topeka, Watertown (US)	PM (fixed monitoring)	Deaths (all-cause)	Cox proportional hazards model stratified by movers and non-movers to compare the RRs for the entire cohort.	Small numbers of movers, movers' group is younger and received higher education than non-movers, only 6 cities (one city has higher mobility), not associated with change of exposure.

Abbreviations: BMI (body mass index), BP (blood pressure), CHD (coronary heart disease), DBP (diastolic blood pressure), FeNO (fractional exhaled nitric oxide), FEV_1 (forced expiratory volume in 1 s), HRV (heart rate variability), IQR (interquartile range), LUR model (land use regression model), LBW (low birth weight), LF (lung function), MMEF (maximal midexpiratory flow), MVV (maximum voluntary ventilation), NY (New York state), PEF (peak expiratory flow), PEFR (peak expiratory flow rate), PP (pulse pressure), PTB (preterm birth), SBP (systolic blood pressure), SGA (small for gestational age).

Two articles included in the review include research on the short- term health effects of ambient air pollution exposure conducted among students in Beijing as part of the Healthy Volunteer Natural Relocation (HVNR) study. Risk of bias was assessed as 'probably high' for both articles due to the lack of blinding and concerns that the analysis did not adequately address confounding and effect modification. Wu *et al.* examined blood pressure among 39 male students who completed the first year of their studies at a suburban campus and then moved to an urban campus for their second year (Wu et al., 2013). In this study, concentrations of gaseous air pollutants including CO, NO_x, and NO_2 and levels of several traffic related $PM_{2.5}$ fractions were higher during the suburban period than in the urban periods. Overall levels of $PM_{2.5}$ for the three periods were: 82.0 µg/m^3 ± SD 46.6 (suburban campus), 78.1 µg/m^3 ± 72.5 (urban campus period 1) and 59.9 µg/m^3 ± 40.3 (urban campus period 2). Systolic blood pressure (SBP) and pulse pressure (PP) were significantly higher during the urban than the suburban periods. Analyses also examined the association between SBP or DBP and PM fractions, NO_x, and NO_2 during the 1–3 days before study visits (again, not a test of relocation effect). An interquartile range (IQR) increase of 51 µg/m^3 in $PM_{2.5}$ was associated with a 1.08 mmHg (95% CI: 0.17–1.99) increase in systolic blood pressure and 0.96 mmHg (0.31–1.61) increase in diastolic blood pressure.

In a second HVNR article, Wu et al. followed 21 male students who moved campus during their second university year (Wu et al., 2014). Lung function (FEV_1, FVC, $FEF_{25\text{-}50}$) and respiratory symptoms were compared while the students were in the suburban campus and during two periods in the urban campus. $PM_{2.5}$ concentrations were marginally higher during at the suburban campus (82.1 µg/m^3 ± SD 68.0) than during urban period 1 (78.9 µg/m^3 ± 86.2) and appreciably higher than during urban period 2 (60.5 µg/m^3 ± 59.3). Formal statistical comparison of lung function in relation to the relocation periods was not presented, but morning and evening values of FEV_1 and PEFR showed progressive improvement from the suburban, to urban 1 and then urban 2 monitoring periods (in line with the trend of reducing $PM_{2.5}$. The study did however also report associations of $PM_{2.5}$ with morning and evening PEFR and FEV_1 using a range of time lags from 1 h to 7 days and found evidence of these short-term correlations (not relocation effects) on evening PEFR and on morning and evening FEV_1.

Sakai *et al.* (risk of bias assessment 'probably high') studied 39 men who sailed from Japan to Antarctica for a one year work assignment (Sakai et al., 2004). Serological markers of inflammation and lung function were tested seven times: the day the team departed Japan, four times while in Antarctica, two days after departing Antarctica and just after returning to Japan.

Table 2

$PM_{2.5}$ was 99% lower in Antarctica than in Japan. While study subjects were in Antarctica, there was evidence of decrease in circulating leukocytes (total, segmented polymorphonuclear leukocytes (PMN), band-formed PMNs and monocytes) along with lower levels of interleukin-6 (IL-6) but no clear evidence of lower granulocyte colony stimulating factor (G-CSF). None of the measured indicators of pulmonary function including FEV_1, PEFR, forced vital capacity (FVC) and forced expiratory flow rate (FEF_{25-75}) changed appreciably during the study except for maximum voluntary ventilation (MVV), which showed some evidence of improvement in Antarctica.

Studies of pregnancy outcome

Three articles describe studies of pregnancy outcome of mothers who relocated during their pregnancy. Ambient pollutant levels were reported for the patients' entire pregnancies but pollutant levels before and after relocation were not explicitly reported in these studies. In two of these studies, the main focus on mobility was the effect on exposure assessment. Madsen et al. (risk of bias assessment 'probably low') studied term birth weight, low birth weight (LBW) and small for gestational age (SGA) in a Norwegian cohort of mother-singleton baby pairs (Madsen et al., 2010). Ambient pollutant exposure for participants was modelled based on home address and change of address reporting during the study. There was no clear evidence after confounder adjustment of association between traffic air pollution (NO_2, PM_{10} and $PM_{2.5}$) at home and work addresses assessed by dispersion model or monitoring station and birth weight or SGA. Sensitivity analyses included stratification according to whether the mother had changed address during pregnancy and found results in this group to be broadly similar to the wider cohort. Women who moved while pregnant had lower overall exposure to ambient air pollution than non-movers, and were on average younger, more often nulliparous and of non-western ethnicity, and had lower education.

Pereira *et al*. (risk of bias assessment 'probably low') conducted a prospective cohort study among mother-baby pairs in Connecticut, USA to examine the association between residential mobility, PM_{10} exposure during the pregnancy and low birth weight, pre-term birth (PTB) and SGA (Pereira et al., 2016). Eleven percent of the cohort moved during their pregnancy and those who moved tended to move to lower PM_{10} locations. A majority (87%) of the cohort lived within 20 km of an ambient air pollution monitor and exposure was estimated based on inverse distance weighted (IDW) average of all ambient monitors within buffer distances of 20 km, 40 km, and 100 km from the residential address. Compared with women that did not move, women who moved during pregnancy did not have an elevated risk of PTB (RR 1.03, 95% CI: 0.80, 1.31) or a LBW baby (RR 0.90, (0.51, 1.48)) but they did have a *higher* risk of an SGA birth (RR 1.40, (1.18, 1.67)). However, low birth weight was associated with PM_{10} exposure in the second trimester of pregnancy and the entire pregnancy with odds ratios for a 1 $\mu g/m^3$ increase in PM_{10} of 1.09 (1.04, 1.14) and 1.08 (1.02, 1.14) respectively. Small for gestational age was also associated with PM_{10} exposure in second trimester (odds ratio (OR) 1.02, 95% CI: 1.00–1.04) and whole pregnancy (OR 1.03, (1.01–1.05)).

A further study, Liang *et al.* (risk of bias assessment 'probably high') compared the occurrence of pre-term birth among local residents and migrants to seven Chinese cities in the Pearl River Delta region of southern China, 2015–2017 in a retrospective cohort study (Z. Liang et al., 2019). Ambient air pollution monitoring data was used to identify exposure in the study and mean pollutant levels by trimester were reported for the cohort. They reported stronger air pollution-PTB association among migrants than the local residents with hazard ratios (HRs) for exposure during the entire pregnancy being, respectively, 1.56 (95% CI: 1.50, 1.63) and 0.98 (0.93, 1.02) for each 10 $\mu g/m^3$ increase in $PM_{2.5}$, 1.32 (1.27, 1.39) and 1.18 (1.12, 1.23) for each 10 ppb increase in O_3, and 1.48 (1.40, 1.57) and 0.99 (0.93, 1.05) for each 10 $\mu g/m^3$ increase in SO_2. Associations with NO_2 were not different in migrants and local residents. A sensitivity analysis was conducted that examined the HRs among local residents and migrants separately for conception season, temperature, and relative humidity. No direct analysis presented of PTB in

Table 2

relation to the fact of relocation or the relocation change in AP due to change in air pollution vs effect modification.

Mortality and hospital admissions

Four studies focused on the health impacts of long-term relocations and ambient air pollution. Two cohort studies (one of Medicare recipients and one of military families) used relocation as effectively random change in environment to provide unconfounded estimates of air pollution effects.

Awadh *et al.* (risk of bias assessment 'low') examined mortality and ambient $PM_{2.5}$ among a large cohort of more than 12 million Americans aged 65 years or greater enrolled in the US Medicare program (Awad et al., 2019). Restricting analysis to the >10 million people who changed residential ZIP code allowed a design with randomization of exposure, assuming the choice of new ZIP code is unrelated with confounders, as was indicated by the distribution of measured covariates in relation to the change in exposure. The association between $PM_{2.5}$ and mortality was analyzed by proportional hazards models stratified on the ZIP code of origin with inverse probability weights to control for individual and ecological confounders at the new ZIP code. The findings indicated a hazard ratio for a 10 $\mu g/m^3$ increase in $PM_{2.5}$ of 1.21 (95% CI: 1.20, 1.22) for the white population and 1.12 (1.08, 1.15) for the black population. The study also provided evidence of association at concentrations below current US limits for $PM_{2.5}$.

A similar principle was behind a study by Lleras-Muney (risk of bias assessment 'probably low') who studied respiratory hospitalization among children under 5 years' age with at least one parent in the U.S. military stationed domestically in the U.S. (Lleras-Muney, 2010). About a third of U.S. army families move in a given year and, within rank and occupation, all members are equally likely to be relocated to a particular base. Thus, families move to a high- or low-pollution area in a manner that should be (and was tested to be) independent of their socioeconomic characteristics. A second advantage of military families is that their living conditions remain relatively constant from base to base so that the variation in the (non-weather/air pollution) environment when they move is comparatively small and unobserved neighborhood characteristics thus not likely to be a large source of bias. Lleras-Muney's analysis found evidence of positive association between O_3 levels and respiratory hospitalizations in children aged 2–5 years overall but no evidence for carbon monoxide (CO), PM_{10}, SO_2, or NO_2. Subgroup analysis for movers yielded smaller and statistically non-significant associations for O_3.

We identified two other cohort studies that examined mortality in relation to a long-term change in exposure from relocation. Gan *et al.* (risk of bias assessment 'probably low') studied a cohort of more than 450,000 adults aged 45–85 years in Vancouver, Canada (Gan et al., 2010), whose exposure to road traffic took account of relocation-related proximity to roads. Compared with adults who lived far from traffic throughout the study, adults who moved closer to traffic had a mortality relative risk (RR) of 1.20 (95% CI: 1.00, 1.43), those who moved away from traffic an RR of 1.14 (0.95, 1.37) and those who consistently lived in a high traffic-related air pollution area the highest relative risk of 1.29 (1.18, 1.41).

Krewski *et al.* (risk of bias assessment 'probably low') reanalyzed data on mortality rates and corresponding ambient $PM_{2.5}$ and sulphate levels in six United States locations originally collected as part of the Harvard Six Cities cohort study (Krewski et al., 2003). Their analysis included comparison of the air-pollution mortality relationship among movers and non-movers. For $PM_{2.5}$ exposure, there was a lower point estimate for all-cause mortality in relation to $PM_{2.5}$ for movers (RR 1.08, 95% CI: 0.67, 1.76) than non-movers (RR 1.3 (1.10, 1.54)) or the entire cohort, although confidence intervals overlapped.

Discussion

This is the first literature review of the health effects of people who relocate from one environment to another of differing air pollution levels. Such studies are a form

Table 2

of natural experiment that is somewhat different in nature from natural experiments in which populations in fixed locations are subject to a change of exposure from some form of policy change or intervention, such as those reported in reviews by Rich *et al.* and Burns *et al.* (Burns et al., 2020; Rich, 2017).

Relocation studies have a number of specific advantages. The first is that they provide evidence about the nature and timing of functional and clinical changes if someone moves between environments of differing air pollution concentrations (Li et al., 2020). This is directly relevant to people who may be posted to locations of differing air quality, including those such as diplomats, military families, employees of international companies and international students whose moves may take them and their families to locations of appreciably higher pollutant concentration than their place of origin. It is also potentially relevant to people with illnesses that may be in part attributable to air pollution when considering the possible benefits of moving to a location of lower ambient air pollution to reduce exposure.

The literature we found in relation to the effects of short-term changes in exposure on physiological outcome, biomarkers or symptoms was small and fairly heterogenous. A unifying feature of the included studies is that they reported the before-after (within-person) change in health outcome in relation to the relocation change. However, with the exception of one study based primarily on biomarkers, we rated all these studies as 'probably high risk of bias' because of lack of separate temporal control and/or the lack of blinding in the assessment of outcome – although two of these studies did include some measurements of objective outcomes. None of them used a non-relocating control group or analyzed the change in outcome in relation to person-level assessment of change in exposure, which would have helped strengthen their interpretation. Nonetheless, their results are broadly consistent with that of other epidemiological and clinical literature in suggesting effects on respiratory and cardiovascular function or other biological parameters within a week or few weeks of relocation to an environment of higher pollution level, or their amelioration in moving from an environment of high to low exposure. The fact that all these relocation studies made measurements of within-person change is also an advantage in eliminating the effect of person characteristics. But without an adequate control group or internal comparisons uncertainties remain whether relocation changes in health outcome are attributable to the effects of air pollution or to some other temporally- correlated aspect of the relocation. One study, by Kinney and Lippmann, gave primary focus to the comparison of the (within-person) change in lung function in relation to the between-location differences in O_3 at the destination environments: they found some evidence for larger deterioration in lung function in those who trained at higher O_3 concentrations (Kinney & Lippmann, 2000).

Comparison of change in health outcome in relation to relocation change in exposure (a change-on-change analysis) was used in a long- term relocation study by Avol *et al.* rated by us as 'probably low risk of bias' (Avol et al., 2001). Based on comparisons of change in annual lung function in relation to change in air pollution, their relatively small study of 110 children indicated that relocation-related increase in PM_{10} (between ages 10 and 15 years of age) was associated with decreased rates of growth in maximal mid-expiratory flow, peak expiratory flow and (of borderline statistical significance) forced expiratory volume in 1 second (FEV_1).

A second major advantage (applicable to longer-term cohort studies) is the potential to use the relocation as a form of randomization of exposure. This was the focus of the paper by Awad *et al*. of Medicare recipients and the paper by Lleras-Muney of compulsory relocation of military families (Awad et al., 2019; Lleras-Muney, 2010). The principle exploited in these studies is that the relocation-related *change* in exposure (i.e. whether to an environment of higher or lower ambient pollution) may be unrelated to important covariates. In both the Awad *et al*. and the Lleras-Muney articles, analyses suggested that covariates were indeed effectively randomized by (independent of) the

Table 2

relocation change in exposure, which therefore offers the possibility of an analytical design that should be less biased by inadequate control for confounding. The experiment of relocation can thus add an important strand of epidemiological evidence that supplements and strengthens other observational epidemiological research of air pollution and health. A limitation is that the approach works best if the cohorts are very large with large numbers of relocations without any systematic selection of the movements.

One further cohort study by Gan *et al.* made comparisons of the air pollution-health outcome association in relation to mover status, but mainly to improve or test (as part of sensitivity analyses) differences in exposure classification (Gan et al., 2010). Taking account of relocation-related assessment of exposure to road traffic was useful in assessing the impact of exposure to traffic on coronary heart disease risk.

The three studies of pregnancy outcome in births to mothers who moved during pregnancy used relocation to attempt improve exposure classification for the trimesters of pregnancy. However, neither Madsen *et al*. nor Pereira *et al.* gave clear evidence of difference in the air pollution-pregnancy outcome relationship of those who did and did not move during pregnancy (Madsen et al., 2010; Pereira et al., 2016). And the study of Liang *et al*., which did report a higher hazard ratio for pre-term birth in relation to $PM_{2.5}$, O_3 and SO_2 for migrants to the Pearl River Delta cities compared with local urban residents, cannot be confidently interpreted as an effect of change in air pollution – although the authors suggested that one possible explanation is that migrants tend to come from lower air pollution environments and so may be less adapted to the high levels air pollution exposure in urban areas (Z. Liang et al., 2019).

Two other cohort studies were identified in the review process that did not meet the PECOS inclusion criteria and were not included in the literature review. Results from these two mortality studies primarily focused on the comparison of health effects in non-movers compared to the entire cohort. Beelen *et al.* used data collected in the European Study of Cohorts for Air Pollution Effects (ESCAPE) project which includes 367,251 adults from 22 cohorts in 13 European countries with enrolment beginning in 1995 (Beelen et al., 2014). The analysis examined ambient $PM_{2.5}$, PM_{10}, and NO_2 data as well as traffic intensity and mortality due to natural causes among the cohort. The pooled hazard ratio (HR) of death due to natural causes was greater for non-movers, pooled HR = 1.10 (95% CI: 1.02–1.20) per 5 $\mu g/m^3$ $PM_{2.5}$, than for the entire cohort, pooled HR = 1.06 (95% CI: 1.0–1.12) per 5 $\mu g/m^3$for the entire cohort. Results were not associated with change of exposure and timing of the relocation was not considered in the analysis. Brunekreef *et al.* conducted a nested case-cohort study within the established Netherlands Cohort Study (NLCS) and compared the air-pollution mortality relationship among those who did not move with that of the whole cohort (Brunekreef et al., 2009). The associations were generally stronger in the non-movers than the entire cohort – an observation that may be related to more accurate exposure assessment for those who did not move location. Among the movers, point estimates were above 1.0 for natural all-cause, cardiopulmonary, cardiovascular, respiratory, lung cancer and non-cardio-pulmonary non-lung cancer mortality in relation to background black smoke, traffic intensity in a 100 m buffer of home and overall black smoke, but confidence intervals included 1 except for respiratory mortality. These studies suggest mortality may be lower in movers than non-movers although and further review of the data is needed to substantiate this theory.

The principal limitations of our literature relate to the small number and heterogeneity of the studies identified, and the fact that many of the studies of short- and long-term changes in exposure on physiological outcome, biomarkers or symptoms had design weaknesses. We outline in Table 4 a number of suggested design principles for future studies that would help strengthen their epidemiological interpretation. Although practical consideration may mean that it is not possible to include all these design principles, we believe it is worth attempting to improve the quality of evidence from short-term relocation

Table 2

studies for the insights they provide from their quasi-experimental designs, including on the nature and timing of functional changes.

Conclusions

In conclusion, the literature of relocation studies for studying the health effects of air pollution effects remains limited and very heterogenous in design and quality. However, relocation studies can be advantageous for epidemiological research. The possibility to examine air pollution relationships with reduced confounding has been explored in papers with relatively low risk of bias. Other studies have provided evidence on the nature and timing of functional short-term effects of changes in air pollution exposure, which, although at probably high risk of bias, provide a useful adjunct to other epidemiological studies. There would be value in expanding air pollution research that capitalizes on the advantages of relocation studies, but attention is needed to improve potential bias and confounder control in studies examining the effects of short-term relocations to environments of different air pollution levels.

Table 3 Summary of relocation studies assessing change in health outcomes and air pollution (n = 15).

Author (Year)	Participants and relocation	Follow-up	Comparison	Finding	Risk of bias
Short-term relocations of less than 6 months (n = 4)					
Vilcassim et al. (2019)	34 non-smoking young adult travelers from New York to (higher $PM_{2.5}$) destinations around the world for ≥1 week	FEV_1, PEFR, BP, HR, HRV, symptoms • Week before travel • First week after arrival in destination city • First week after return to NY	Within-person (before- after relocation)	Within a week of arrival in higher $PM_{2.5}$ destination city • Lung function (FEV_1 and PEFR) reduced, with strongest association between morning $PM_{2.5}$ increase and evening FEV_1 increase • Heart rate increased • Heart rate variability reduced • Increased respiratory symptoms • Little change in BP Most effects reversed within week of return to NY	Probably high
Lin et al. (2019)	26 healthy non-smoking California university students who travelled to Beijing for 10 weeks	Urine and blood samples for biomarkers of lipid peroxidation and inflammation, and PAH metabolites • Before travel • 6 or 8 weeks after arriving in Beijing • 4–7 weeks after return to USA	Within-person (before- after relocation)	6–8 weeks after arrival in higher $PM_{2.5}$ Beijing: • Systemic pro-oxidative and proinflammatory biomarkers higher • Changes in urinary PAH • Effects partially reversed after returning from travel	Probably low
Renzetti et al. (2009)	37 untreated allergic asthmatic children from an Italian city who joined school camp in rural area for 1 week	PEFR, nasal eosinophils, FeNO, urinary leukotriene E4 • Before relocation • 7 days after relocation	Within-person (before- after relocation)	Within a week of travel to camp (lower $PM_{2.5}$): • Increase in PEFR • Decrease in nasal eosinophils and FeNO • Improved lower airway function	Probably high
Kinney and Lippmann (2000)	72 US West Point military cadets who underwent 5 weeks outdoor training at four locations in the US, including a site with higher O_3 level, Fort Dix, New Jersey	FEV_1, FVC, FEF_{25-75}, respiratory symptoms: • Before training (April 1990) and • 4 weeks after training (late August-early September 1990)	Between-person comparison of relocation- change in LF in relation to destination O_3	Highest mean O_3 in Fort Dix, low levels of PM_{10} and SO_2 in all sites. After 5 weeks of outdoor training: • Decline in mean FEV_1 and FEF_{25-75} in all locations • Increase in sore throat, cough, chest tightness among all cadets • Deterioration of lung function was larger among cadets who trained at higher O_3 in Fort Dix compared with the other three locations, but difference was not statistically significant	Probably high
Long-term relocations of at least 6 months (n=11)					
Avol et al. (2001)	110 Californian children aged 10 years at recruitment, 15 years at follow-up, who relocated to another US location of lower or higher PM_{10}	FEV_1, FVC, MMEF, PEFR, respiratory symptoms measured at: – study entry in 1993/1994 – follow up in 1998	Between-person comparison of change in annual LF growth rate in relation to change in AP	• Relocation-related increase in PM_{10} associated with decreased rates of annual growth in MMEF, PEFR and (of borderline statistical significance) FEV_1. No association for FVC. • Indicative trends that effect greater in those who migrated >3 years before follow-up visit • Point estimates suggested increases in NO_2 and O_3 also associated with reduced lung function growth rates but CIs included null	Probably low
Wu et al. (2013)	39 healthy male university students in China who relocated summer 2010 from a suburban to an urban campus in Beijing	Twice weekly BP measurements in *Pre-move* • Suburban: Apr–Jun 2010 *Post-move (moved summer 2010)* • Urban 1: Sep–Nov 2010 • Urban 2: Apr–Jun 2011	Within-person (before- after relocation)	Ranking of $PM_{2.5}$ concentrations was suburban (highest) > urban 1 > urban 2 (lowest). • Comparison of periods (indicator of location) by *t*-test only; mixed findings for change in BP • Analyses also conducted of BP variables in association with preceding day $PM_{2.5}$ but not directly relevant to the relocation effect	Probably high (for relocation effect)
Wu et al. (2014)	21 healthy male university students in China who relocated in Aug 2010 from a suburban to urban campus in Beijing	Twice daily PEFR and FEV_1 *Pre-move* • Suburban: Apr–Jun 2010 an Post-move (moved summer 2010) • Urban 1: Sep–Nov 2010 • Urban 2: Apr–Jun 2011	Within-person (before- after relocation)	Ranking of $PM_{2.5}$ concentrations was suburban (highest) > urban 1 > urban 2 (lowest). Periods with lower $PM_{2.5}$ (i.e. relocation effect) associated with: • Increased FEV_1 and PEF • Effects modified by temperature	Probably high

Sakai et al. (2004)	39 male workers who travelled by ship from Japan to Antarctica for 1 year	FVC, FEV_1, FER, FEF_{25-75}, PEFR, MVV; leukocyte counts and differential; G-CSF, IL-6 measured on:	Within-person (before- after relocation)	PM decreased by >99% from Japan to Antarctica	Probably high

Summary of relocation studies assessing change in health outcomes and air pollution (n = 15).

(*continued on next page*)

Table 3 (*continued*)

Author (Year)	Participants and relocation	Follow-up	Comparison	Finding	Risk of bias
		• Day 1 of outward voyage. • Days 109, 210, 271, 354 (in Antarctica). • Day 447 (day 2 of homeward voyage). • Day 516 (after arrival back in Japan)		• Little change in lung function except for selective differences for MVV but no clear pattern • Decrease during Antarctic phase in banded and segmented neutrophils but not total leukocyte counts • Decrease in IL-6 but not granulocyte-colony stimulating factor in Antarctica	
Madsen et al. (2010)	25,229 mother-(singleton) baby pairs in Norway who had information on residential move (s) while pregnant	Pregnancy outcomes: term birth weight, LBW and SGA	Pollution-outcome response in movers *vs* non- movers	• No clear evidence for association between air pollution (NO_2, $PM_{2.5}$, PM_{10}) and LBW or SGA in movers or non-movers after confounder adjustment • No direct test of effect of change in AP environment	Probably low
Pereira et al. (2016)	9587 pregnant US mothers in 1 of 4 health cohorts (1988–2008)	Pregnancy outcomes: LBW, SGA, PTB	Mover *vs* non-mover (relocation effect) and of pollution-outcome response	• Movers had a *higher* risk of an SGA birth (RR 1.40, 95% CI: 1.18, 1.67) than non-mover but not of delivering preterm (RR 1.03, 95% CI: 0.80, 1.31) or LBW (RR 0.90, 95% CI: 0.51, 1.48). Pregnant women tended to move to locations with lower $PM_{10,}$ but effect of relocation not analyzed in relation to change in pollution. • For all outcomes, there was negligible difference in effect sizes corresponding to exposures calculated with first, last and full address histories.	Probably low
Liang et al. (2019)	628,439 singleton pregnant mothers who moved to Pearl River Delta while pregnant	Pregnancy outcome: PTB	Pollution-outcome response in movers *vs* non- movers	• Hazard ratios of PTB higher (and statistically significant) in migrants than local urban residents in relation to $PM_{2.5}$, O_3 and SO_2 based on whole pregnancy exposure; point estimate of NO_2 association below 1 for both groups. • Much smaller and not statistically significantly differences in HRs for any individual trimester of pregnancy or for the 2-weeks prior to delivery. • Migrants reported to live in places with lower air pollution before moving to urban areas, but data not tabulated. • No direct analysis presented of PTB in relation to the fact of relocation or the relocation *change* in AP	Probably high
Awad et al. (2019)	10,679,150 US adults 65 years enrolled in Medicare who moved residence from one ZIP-code to another during follow-up	Deaths (all causes) in cohort from 2000 to 2012	Analysis of AP-mortality relationship restricted to movers to achieve effective randomization of exposure	Hazard ratio for a 10 μg m^{-3} (relocation-associated) increase in $PM_{2.5}$ was: • 1.21 (95% CI 1.20, 1.22] among whites • 1.12 (95% CI 1.08, 1.15) among blacks	Low
Lleras-Muney (2010)	159,275 children ≤5 years of military parents who moved residences every 2–4 years	Overnight hospitalization for respiratory conditions, 1989 to 1995, in relation to year estimate of CO, PM_{10}, SO_2, NO_2, O_3	Within-person analysis of hospital admission in relation to year AP. Sub-group analysis of movers	• Respiratory hospitalizations in children aged 2–5 higher in year-locations with higher O_3 • Subgroup analysis for movers yielded smaller and statistically non-significant associations for O_3 • No evidence for similar association for any other pollutants (CO, PM_{10}, SO_2, NO_2)	Probably low

Gan et al. (2010)	450,283 Vancouver residents who did or did not move during 4 years follow up	CHD deaths in cohort recruited in 1999 with exposure recorded 1994 to 1998, morality from 1999 to 2002	Between-person analysis of risk in relation to relocation change in traffic exposure	Compared with the subjects consistently living away from road traffic, relative risk (RR) and 95% CI of CHD mortality varied as follows: • Among those who were consistently exposed, living closer to road traffic: RR 1.29 (1.18–1.41) • Those who moved closer to traffic: RR 1.20 (1.00–1.43) • Those who moved away from traffic: RR 1.14 (0.95–1.37)	Probably low
Krewski et al. (2003)	8111 white adults in the US Six Cities Study who moved within the United States during the follow up period	Deaths (all causes) in cohort enrolled in the study from 1974 to 1977 with deaths recorded up to 1991	Comparison of AP- mortality relationship among movers *vs* non- movers	• Lower point estimate RR of all-cause mortality in relation to PM$_{2.5}$ for movers (RR = 1.08, 95%CI 0.67, 1.76) than non-movers (1.3, 95%CI 1.10, 1.54) or the entire cohort (RR = 1.26) but CIs overlapped • Movers were younger and better educated than non-movers	Probably low

Abbreviations: AP (air pollution), CHD (coronary heart disease), CI (confidence interval), CVD (cardiovascular disease), FeNO (fractional exhaled nitric oxide), FEV$_1$ (forced expiratory flow in 1 s), FEF$_{25-75}$ (forced expiratory flow rate between 25% and 75% of forced vital capacity), FER (forced expiratory flow rate), FVC (forced vital capacity), G-CSF (granulocyte colony-stimulating factor), HR (heart rate or hazard ratio depending on context), HRV (heart rate variability), IL-6 (interleukin-6), LBW (low birth weight), LF (lung function), MMEF (maximal mid-expiratory flow), MVV (maximum voluntary ventilation), PEFR (peak expiratory flow rate), PAH (polyaromatic hydrocarbons), PTB (preterm birth), RR (relative risk), SGA (small for gestational age).

Table 4 Suggested principles of design and analysis for relocation studies of physiological outcome, biomarkers, or symptoms.

- Use a (non-relocating) comparison group as control for before-after change and/or use recorded air pollution changes for internal comparison of change in outcome *vs* change in exposure (*change-on-change* analysis)
- Where possible, use objective measures of outcome recorded using standard procedures
- As far as possible, blind of participants and investigators to pollutant concentrations and results of outcome measurements
- Record and report pollutant concentrations before and after relocation, ideally using individualized measures of exposure/ambient concentration
- Use participant selections and/or covariate data recording and analysis to minimize, or adjust for, differences in personal characteristics in analysis of before- after change for each target group of interest
- Document an assessment of potential time-varying confounders, including temperature and activities, and incorporate corresponding data recording and analysis
- Provide clear documentation of the time-course of change in outcome in relation to the change in exposure/ambient concentrations
- Use multiple repeat measures to provide more statistically stable and representative assessment of change in pollution and health outcome
- Ideally, measure the change in outcome before, during and after relocation (i.e. including return to the original environment)
- Reporting of both a (binary) analysis of the relocation effect and of the change in outcome *vs* change in exposure/ambient concentration adjusted for individual-level confounders

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envpol.2021.118314.

Author statement

Leslie Edwards: Conceptualization, Methodology, Data curation, Writing – original draft preparation. **Paul Wilkinson:** Supervision, Methodology, Writing – Reviewing and Editing. **Gemma Rutter:** Data curation, Writing – Reviewing and Editing. **Ai Milojevic:** Supervision, Data curation, Writing – Reviewing and Editing.

References

Avol, E.L., Gauderman, W.J., Tan, S.M., London, S.J., Peters, J.M., Dec 1 2001. Respiratory effects of relocating to areas of differing air pollution levels. Am. J. Respir. Crit. Care Med. 164 (11), 2067–2072. https://doi.org/10.1164/ajrccm.164.11.2102005.

Awad, Y.A., Di, Q., Wang, Y., et al., 2019. Change in PM2.5 exposure and mortality among Medicare recipients: combining a semi-randomized approach and inverse probability weights in a low exposure population. Environ. Epidemiol. Aug 3 (4), e054. https://doi.org/10.1097/EE9.0000000000000054.

Beelen, R., Raaschou-Nielsen, O., Stafoggia, M., et al., 2014. Effects of long-term exposure to air pollution on natural-cause mortality: an analysis of 22 European cohorts within the multicentre ESCAPE project. *Lancet*. Mar 1 383 (9919), 785–795. https://doi.org/10.1016/S0140-6736(13)62158-3.

Brunekreef, B., Beelen, R., Hoek, G., et al., 2009. Effects of long-term exposure to traffic- related air pollution on respiratory and cardiovascular mortality in The Netherlands: the NLCS-AIR study. Res. Rep. Health Eff. Inst. Mar 139, 5–71 discussion 73-89.

Burns, J., Boogaard, H., Polus, S., et al., 2020. Interventions to reduce ambient air pollution and their effects on health: an abridged Cochrane systematic review. Environ. Int. Feb 135, 105400. https://doi.org/10.1016/j.envint.2019.105400.

Castelli, F., Jul 1 2018. Drivers of migration: why do people move? J. Trav. Med. 25 (1) https://doi.org/10.1093/jtm/tay040.

Cohen, A.J., Brauer, M., Burnett, R., et al., 2017. Estimates and 25-year trends of the global burden of disease attributable to ambient air pollution: an analysis of data from the Global Burden of Diseases Study 2015. Lancet 389, 1907–1918. https://doi.org/10.1016/S0140-6736(17)30505-6. In press.

Cummings, C., Pacitto, J., Lauro, D., et al., 2015. Why people move: understanding the drivers and trends of migration to Europe. Overseas Dev. Inst. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/542028/understanding-drivers-migration-Europe.pdf.

Gan, W.Q., Tamburic, L., Davies, H.W., Demers, P.A., Koehoorn, M., Brauer, M., 2010. Changes in residential proximity to road traffic and the risk of death from coronary heart disease. Research Support, Non-U.S. Gov't. *Epidemiology*. Sep 21 (5), 642–649. https://doi.org/10.1097/EDE.0b013e3181e89f19.

Huangfu, P., Atkinson, R., 2020. Long-term exposure to NO2 and O3 and all-cause and respiratory mortality: a systematic review and meta-analysis. *Environ Int*. Nov 144, 105998. https://doi.org/10.1016/j.envint.2020.105998.

Johnson, P.I., Koustas, E., Vesterinen, H.M., et al., Jul-Aug 2016. Application of the Navigation Guide systematic review methodology to the evidence for developmental and reproductive toxicity of triclosan. Environ. Int. 92–93, 716–728. https://doi. org/10.1016/j.envint.2016.03.009.

Kinney, P.L., Lippmann, M., May-Jun 2000. Respiratory effects of seasonal exposures to ozone and particles. Comparative Study Research Support, U.S. Gov't, Non-P.H.S. Archiv. Environ. Health 55 (3), 210–216.

Krewski, D., Burnett, R.T., Goldberg, M.S., et al., 2003. Overview of the reanalysis of the harvard six cities study and American cancer society study of particulate air pollution and mortality. Review. J. Toxicol. Environ. Health Part A 66 (16–19), 1507–1551. https://doi.org/10.1080/15287390306424.

Li, X., Chen, H., Li, Y., 2020. The effect of air pollution on children's migration with parents: evidence from China. Environ. Sci. Pollut. Res. Int. Apr 27 (11), 12499–12513. https://doi.org/10.1007/s11356-020-07831-3.

Liang, Z., Yang, Y., Li, J., et al., 2019. Migrant population is more vulnerable to the effect of air pollution on preterm birth: results from a birth cohort study in seven Chinese cities. Int. J. Hyg. Environ. Health. Aug 222 (7), 1047–1053. https://doi.org/10.1016/j.ijheh.2019.07.004.

Lin, Y., Ramanathan, G., Zhu, Y., et al., 2019. Pro-oxidative and pro-inflammatory effects after traveling from Los Angeles to Beijing: a biomarker-based natural experiment. Circulation 20doi. https://doi.org/10.1161/CIRCULATIONAHA.119.042054.

Liu, C., Chen, R., Sera, F., et al., 2019. Ambient particulate air pollution and daily mortality in 652 cities. N. Engl. J. Med. 381, 705–715. https://doi.org/10.1056/ NEJMoa1817364.

Lleras-Muney, A., 06/01 2010. The needs of the army: using compulsory relocation in the military to estimate the effect of air pollutants on Children's health. J. Hum. Resour. 45doi:10.1353/jhr.2010.0016.

Madsen, C., Gehring, U., Walker, S.E., et al., 2010. Ambient air pollution exposure, residential mobility and term birth weight in Oslo, Norway. Environ. Res. May 110 (4), 363–371. https://doi.org/10.1016/j.envres.2010.02.005.

Moher, D., Liberati, A., Tetzlaff, J., Altman, D.G., Group, P., Jul 21 2009. Preferred reporting items for systematic reviews and meta-analyses: the PRISMA statement. Bmj 339, b2535. https://doi.org/10.1136/bmj.b2535.

Pereira, G., Bracken, M.B., Bell, M.L., 2016. Particulate air pollution, fetal growth, and gestational length: the influence of residential mobility in pregnancy. Environ. Res. May 147, 269–274. https://doi.org/10.1016/j.envres.2016.02.001.

Pope 3rd, C.A., Coleman, N., Pond, Z.A., Burnett, R.T., 2020. Fine particulate air pollution and human mortality: 25+ years of cohort studies. Environ. Res. Apr 183, 108924. https://doi.org/10.1016/j.envres.2019.108924.

Rajagopalan, S., Al-Kindi, S.G., Brook, R.D., Oct 23 2018. Air pollution and cardiovascular disease: JACC state-of-the-art review. J. Am. Coll. Cardiol. 72 (17), 2054–2070. https://doi.org/10.1016/j.jacc.2018.07.099.

Renzetti, G., Silvestre, G., D'Amario, C., et al., 2009. Less air pollution leads to rapid reduction of airway inflammation and improved airway function in asthmatic children. Research Support, N.I.H., Extramural. *Pediatrics*. Mar 123 (3), 1051–1058. https://doi.org/10.1542/peds.2008-1153.

Rich, D.Q., 2017. Accountability studies of air pollution and health effects: lessons learned and recommendations for future natural experiment opportunities. Review. Environ. Int. Mar 100, 62–78. https://doi.org/10.1016/j.envint.2016.12.019.

Sakai, M., Sato, Y., Sato, S., et al., 2004. Effect of relocating to areas of reduced atmospheric particulate matter levels on the human circulating leukocyte count. J. Appl. Physiol. 97, 1774–1780. https://doi.org/10.1152/japplphysiol.00024.2004. United States Department of State. Popular topics - medical clearances. https://www. state.gov/popular-topics-medical-clearances/. (Accessed 12 May 2020).

United Nations, 2020. International Migration 2019 Report . https://migrationnetwork.un.org/resources/international-migration-2019-report.

Vilcassim, M.J.R., Thurston, G.D., Chen, L.C., et al., Jun 11 2019. Exposure to air pollution is associated with adverse cardiopulmonary health effects in international travellers. J. Trav. Med. 26 (5), 11. https://doi.org/10.1093/jtm/taz032.

Wu, S., Deng, F., Huang, J., et al., 2013. Blood pressure changes and chemical constituents of particulate air pollution: results from the healthy volunteer natural relocation (HVNR) study. *Environ Health Perspect*. Jan 121 (1), 66–72. https://doi. org/10.1289/ehp.1104812.

Wu, S., Deng, F., Hao, Y., et al., 2014. Fine particulate matter, temperature, and lung function in healthy adults: findings from the HVNR study. Research Support, Non-U. S. Gov't. *Chemosphere*. Aug 108, 168–174. https://doi.org/10.1016/j. chemosphere.2014.01.032.

3.3 Postscript to literature review

The literature review helped inform the focus on $PM_{2.5}$-related mortality in the modeling study included in Chapter 6 of my thesis. Risk coefficients and other statistics published in articles identified in the literature review were not directly used in my health modeling study.

My original contributions to this research and publication include (1) writing the search criteria and conducting the systematic literature searches in Medline, Global Health and Embase that yielded the published articles analyzed, (2) importing all abstracts and published articles into the Covidence software used in the review process, (3) leading the review of all abstracts for consideration to be included in the literature review, (4) leading the review of the full research articles for consideration to be included in the literature review, (5) writing the first draft of the manuscript, (6) incorporating advice from co-authors into subsequent drafts of the manuscript, (7) creation and maintenance of an Excel database to track input from all co-authors on the selection of articles for the literature review and co-authors' ratings on data quality and risk of bias in the 15 articles included in the literature review, (8) preparing all tables and figures included in the manuscript, (9) submitting the manuscript and related materials to the journal *Environmental Pollution* for consideration, and (10) updating the manuscript to reflect feedback from the journal's editors. Further details about my contributions to the research are available on the Research Paper Cover Sheet (Item D) included in Section 3.2 of my thesis.

Following the findings that particulate matter, typically $PM_{2.5}$, was the pollutant reported in a majority of the articles identified in the literature review as well as the prior scientific evidence published on the health effects of $PM_{2.5}$ exposure, $PM_{2.5}$ was chosen as the exposure to be examined for diplomats in the research described in Chapters 4, 5 and 6 of my thesis (Cohen et al., 2017; C. Liu et al., 2019; Rajagopalan et al., 2018). Another reason I selected to focus on $PM_{2.5}$

in my thesis was the US Department of State's focus on $PM_{2.5}$ and related prioritization of $PM_{2.5}$-related research as recommended by the US National Academies of Science's Standing Committee on the Medical and Epidemiological Aspects of Air Pollution on US Government Employees and Family Members (National Academies of Science, 2021).

Since the publication of this literature review of the health effects of ambient air pollution exposure among persons who have relocated, two relevant papers have been published. A study conducted by Chen *et al.* has direct relevance to my literature review and would have been included in my search, had this article been published earlier (Chen et al., 2021). A study by Saucy et al. provides important information on natural experiments that used relocations as a source of exposure variability, though it does not examine causal associations between change of air pollution exposure and health and likely would not have been included in the literature review (Saucy et al., 2023).

Chen *et. al.* conducted a quasi-experimental study among members of the Canadian Census Health and Environment Cohort who relocated from an original residential address to a new residential address for more than five years during 1996-2006, with ambient $PM_{2.5}$ noted at both addresses (Chen et al., 2021). Annual ambient $PM_{2.5}$ levels were allocated for cohort members at their residential postal code address using satellite observations combined with a global atmospheric chemistry transport model. Grouping $PM_{2.5}$ exposure into three levels (low, intermediate, and high), the analysis included the movers from low and high $PM_{2.5}$ exposure groups at the beginning, to track their moves to low, intermediate, and high $PM_{2.5}$ locations in five or more years. This is a large scale of quasi-experimental study using population-based cohort with 663,100 movers for more than five years relocation. Using a propensity score matching technique with various demographic, socioeconomic, health and environmental characteristics, each mover to a different $PM_{2.5}$ area was matched with up to three participants who moved within the same $PM_{2.5}$ area. The association between changes in $PM_{2.5}$ and mortality was estimated by Cox proportional hazards models with matching weights applied and time on study (in days) as the time scale. Participants who moved from an area with high $PM_{2.5}$ to an area with intermediate $PM_{2.5}$ experienced a 3.3 $\mu g/m^3$ decrease in ambient $PM_{2.5}$ and a 6.8% (95% CI: 1.7%, 11.7%) decrease in natural cause mortality during the 5 years after relocation. Persons who moved from high to low $PM_{2.5}$ experienced a 5.3 $\mu g/m^3$ decrease in ambient $PM_{2.5}$ and a 12.8% (95% CI: 1.3%, 23.0%) decrease in natural cause mortality, with the greatest reduction in cardiometabolic deaths. Changes in mortality among persons who moved to an area with an increase in ambient $PM_{2.5}$ were less conclusive: movers from low to intermediate $PM_{2.5}$ experienced a 2.1 $\mu g/m^3$ increase in $PM_{2.5}$ and a 1.8% (95% CI: -4.1%, 6.9%) change in natural cause mortality and movers from low to high $PM_{2.5}$ experienced a 4.6 $\mu g/m^3$ increase in $PM_{2.5}$ and a 13.2% (95% CI -1.5%, 30.2%) change in natural cause mortality, with the largest increase in deaths due to respiratory conditions. This quasi-experimental study in Canada reported that reductions in mortality for cohort members were associated with reductions in ambient $PM_{2.5}$ arising from residential relocations. Despite several major limitations in this study (lack of adjustment for smoking, household factors and limited generalizability of the study), by design this study eliminated any temporal confounding by chronic trends in outcomes and exposures that most of the studies included in my published literature review did not. Overall, Chen *et al.* is consistent with the three research papers examining mortality rates among long-term relocated populations that were included in my literature review (Awad et al., 2019; Gan et al., 2010; Krewski et al., 2003) with findings indicating an inverse relationship between the change in ambient $PM_{2.5}$ during the relocation and mortality. Importantly, the findings from this Canadian study strengthens the evidence that a change in $PM_{2.5}$ levels, even at relatively low levels, was associated with a change in mortality outcomes.

Saucy *et al.* argued that the studies using relocation as a setting for a natural experiment to examine the causal relationship between change in living environments and health may be biased if the predictors of relocation are not accounted for in the study (Saucy et al., 2023). The authors investigated factors associated with relocation and changes in multiple environmental exposures across life stages using data from Swedish and Dutch adults and birth cohorts. On average, 7% of the participants relocated each year and movers generally relocated to an area with a decrease in ambient air pollution. Predictors of moving differed between the adult and birth cohorts: in the adult cohort studies, moving was associated with younger age, smoking and a lower level of education, but was independent of cardio-respiratory health indicators (hypertension, body mass index, asthma, COPD). In the birth cohort studies, higher parental education and household socioeconomic position were associated with a higher probability of relocation. Interesting, among movers in all cohorts, those with higher socioeconomic position at baseline were more likely to move to a location with better air quality.

The observations by Saucy *et al.* among European cohort study participants are somewhat consistent with the reanalysis of the US Six Cities study (Krewski et al., 2003) included in the published literature review regarding demographic characteristics among movers (typically younger, higher education level). The Saucy *et al.* study is not directly comparable to the studies included in my published literature review as the focus of the Saucy *et al*. study was to identify predictors of relocation while the rationale for relocation among the US diplomatic corps is well understood and was neither a focus of my literature review nor of my doctoral research.

There is a critical correction in my published review paper to address. The published paper included the phrase "roughly 1 in 3 deaths globally, were due to exposure to fine particulate matter smaller than 2.5 µm ($PM_{2.5}$)". Upon further examination of the data, this estimation should be revised to reflect "roughly 7% of deaths globally were due to exposure to fine particulate matter smaller than 2.5 µm ($PM_{2.5}$)" based on the GBD 2019 estimation of 4.1 million $PM_{2.5}$-related deaths among 55.4 million deaths worldwide in 2019 (Sang et al., 2022; World Health Organization, 2020).

3.4 Fulfillment of thesis objectives

The literature review presented in this chapter fulfilled objective 1, as the review described the published articles that examined the impacts of air pollution on mortality and morbidity among populations who relocate between areas with different ambient air pollution concentrations. In this literature review, I investigated the health outcomes, pollutants, time frame of measurable health impacts and the observed magnitude of the reported findings. Changes in respiratory symptoms, testing, or hospitalizations following a relocation were reported in six studies, all of which reported the change in $PM_{2.5}$ and/or PM_{10}. Differences in mortality rates among populations that moved to an area with a change in $PM_{2.5}$, PM_{10} or a change in proximity to traffic were reported in comparison to mortality rates among persons that did not relocate during the study. Panel studies (n=5) were the most common study design among research that reported a change in respiratory health outcomes and all three studies that reported a change in mortality rates were cohort studies. Challenges to quantify the health impacts due to changes in average air pollution exposure in relation to relocations include the limited number of studies identified in the literature review, study design type for the studies focused on respiratory health outcomes and the limited reported on the quantity of change in ambient air pollution in two of the three studies focused on mortality.

4 $PM_{2.5}$ personal exposure and time spent in microenvironments: Natural experiment study of COVID-19 lockdown in Kathmandu

4.1 Introduction

This chapter focuses on the natural experiment study of the personal exposure to $PM_{2.5}$ among four US diplomats living in Kathmandu before and during the COVID-19 lockdown requirements imposed by the government of Nepal in March 2020. The government of Nepal issued a lockdown order in the Kathmandu Valley for 80 days from 24 March to 21 July 2020 (Basnet et al., 2021). Change in the $PM_{2.5}$ mean concentration according to microenvironment and the time spent in various microenvironments were investigated before and during the lockdown period. The study yielded valuable information for the US diplomatic population in Kathmandu to help guide behaviors to reduce $PM_{2.5}$ personal exposure.

US diplomats who work in the US Embassy in Kathmandu spend at least forty hours per week working in an environment with highly filtered air and with indoor $PM_{2.5}$ expected to be near 0 $\mu g/m^3$. US diplomats are provided with air purifiers to use in their residences while they are working in Kathmandu and prior to the COVID pandemic, diplomats' $PM_{2.5}$ personal exposure was expected to be far lower than the ambient $PM_{2.5}$. On 24 March 2020, when US diplomats began working from their residences in Kathmandu, it was expected that their $PM_{2.5}$ personal exposure would increase from the pre-pandemic levels due to spending more time at home and less time at the US Embassy. It was also unknown as to whether diplomats may increase their time spent outdoors, in the backyard of their home, during the lockdown period. The setting for this study is Kathmandu, Nepal with the study participants, US diplomats, who live within one mile (1.5 km) of the US Embassy, in an area with less traffic and lower ambient $PM_{2.5}$ than other parts of the city.

The COVID-19 pandemic provided the opportunity for a natural experiment to examine how $PM_{2.5}$ personal exposure and time in microenvironments changed for US diplomats in Kathmandu, during a period when ambient $PM_{2.5}$ was approximately 40% lower than during the same time period from 2016-2019 (United States Environmental Protection Agency, 2023a). The findings in Kathmandu were similar to those discussed by Shi *et al.* for 9 of 11 cities examined, including New Delhi, but it should be noted that Shi's research examined changes in deweathered and detrended data, with a machine learning random forest model algorithm applied to observed ambient $PM_{2.5}$ data that removed the impact of temperature, wind speed and direction, and relative humidity (Shi et al., 2021). The ambient $PM_{2.5}$ data used in my research was not adjusted for meteorological factors. Sharma *et al.* reported a 43% decrease in ambient $PM_{2.5}$ in 22 cities in India in March to April 2020 compared to the same time period in 2017 to 2019, with an examination of the impact of wind speed and temperature variation on $PM_{2.5}$ examined through modeling (Sharma et al., 2020). Rodriguez-Urrego examined the changes in ambient $PM_{2.5}$ in the 50 most polluted national capital cities, including Kathmandu and New Delhi, during one week before and one week during COVID-related lockdown and quarantine restrictions, and reported a 12% decrease in $PM_{2.5}$ (Rodriguez-Urrego & Rodriguez-Urrego, 2020). Venter *et al*. analyzed $PM_{2.5}$ ambient data from more than 10,000 fixed-site air quality stations in 34 countries from during COVID-19 related lockdown periods from 1 January to 15 May 2020 and reported a 31% (IQR 50%) decrease in the population-weighted mean $PM_{2.5}$ during lockdown compared to the corresponding day's 3 year average from 2016-2019, with $PM_{2.5}$ data that had not been adjusted for meteorological factors (Venter et al., 2020). Ambient $PM_{2.5}$ increased in just two of the 34 countries studied, Australia and Thailand, in early 2020 with increases attributed to smoke from nearby wildfires. The decrease in ambient $PM_{2.5}$ in Kathmandu during the COVID-19 lockdown compared to the observed $PM_{2.5}$ reported on the same day in prior years was similar to that seen in other locations studied with the exception of areas impacted by smoke produced by wildfires.

This analysis was not originally proposed during my Upgrade Seminar on 11 September 2019 as I had no way of knowing that a global pandemic would begin in late 2019 and would not only disrupt my planned research but would disrupt nearly every aspect of society (Singh & Singh, 2020).

This paper addresses research objective (2) conduct repeated personal $PM_{2.5}$ exposure monitoring sessions for 48 hours to characterize individual exposure profiles for US diplomats and family members living in a selected city with high ambient $PM_{2.5}$ and (2a) quantify the $PM_{2.5}$ exposure level for US diplomats and family members, who live in a city with high ambient PM2.5, at the individual level by microenvironment and examine the relationship between the cumulative $PM_{2.5}$ personal exposure and time spent in each microenvironment utilizing a natural experiment opportunity due to the COVID-19 pandemic (before vs during pandemic comparison).

This activity is included as a research paper in chapter 4 and was accepted for publication in the journal *Science of the Total Environment* in December 2020. The supplementary material from this paper is included in Appendix 2.

4.2 Research Paper

The cover sheet and research paper for this activity are included on subsequent pages. The published research paper has been transformed from an Adobe document to MS Word to optimize viewing in my thesis. The published research paper is also available on the following webpage https://www.sciencedirect.com/science/article/pii/S0048969720383698?via%3Dihub .

4.2.1 Research Paper Cover Sheet

London School of Hygiene & Tropical Medicine
Keppel Street, London WC1E 7HT

T: +44 (0)20 7299 4646
F: +44 (0)20 7299 4656
www.lshtm.ac.uk

RESEARCH PAPER COVER SHEET

Please note that a cover sheet must be completed for each research paper included within a thesis.

SECTION A – Student Details

Student ID Number	lsh1514008	**Title**	Ms.
First Name(s)	Leslie		
Surname/Family Name	Edwards		
Thesis Title	$PM_{2.5}$ Exposure and Associated Health Impacts on United States Government Diplomats and Accompanying Family Members With Multiple International Relocations: Exposure Measurement and Health Modeling Study		
Primary Supervisor	Dr. Ai Milojevic		

If the Research Paper has previously been published please complete Section B, if not please move to Section C.

SECTION B – Paper already published

Where was the work published?	Science of the Total Environment		
When was the work published?	23 September 2020		
If the work was published prior to registration for your research degree, give a brief rationale for its inclusion	Not Applicable		
Have you retained the copyright for the work?*	**No**	Was the work subject to academic peer review?	**Yes**

*If yes, please attach evidence of retention. If no, or if the work is being included in its published format, please attach evidence of permission from the copyright holder (publisher or other author) to include this work.

SECTION C – Prepared for publication, but not yet published

Where is the work intended to be published?	
Please list the paper's authors in the intended authorship order:	
Stage of publication	Choose an item.

SECTION D – Multi-authored work

For multi-authored work, give full details of your role in the research included in the paper and in the preparation of the paper. (Attach a further sheet if necessary)	My role and independent contributions to the research included planning the study, ensuring ethical approval, data collection and analytics and developing the manuscript from the original draft to the accepted version of the paper. Specifically, I led efforts to identify funding for the study including acquisition of personal monitors and a fixed site monitor used to ensure proper calibration for the personal monitors and travel funding. I developed a study protocol which included background and rationale for the study, data collection tools, a protocol to prepare personal monitors for each monitoring session, and instructions for personal monitoring data reporting to ensure timely transmission of data from the personal monitors to the cloud-based data storage platform. I developed and submitted materials for the ethical approval of the study both at the London School of Hygiene as well as at the US Department of State and complied with research ethics requirements at both institutions. I led the data curation for the study with input from my PhD supervisors Dr. Ai Milojevic (AM) and Dr. Paul Wilkinson (PW). This included development of the data collection tool used before every personal monitoring session, development of the data platform used to record questionnaire-based data, collaboration with experts who designed the personal monitoring tool to develop a protocol to obtain monitoring data and link that data with the questionnaire-based data such as demographics, use of air purifiers, and mode of transportation to and from work. I collaborated with US Embassy experts to collect details about study participants' housing structure and air purifiers used in the home. I led the data cleaning, data management, and data interpretation for the study.

	I prepared of data visualizations for each personal monitoring session conducted during the study, and other visualizations and data tables for the published article. I wrote the original draft of the manuscript and led the review and editing of the manuscript based on comments from co-authors and feedback from reviewers from the journal. I wrote the first draft of the manuscript including tables and figures and developed to the final version of this paper by incorporating advice from co-authors. I also led the submission process of this paper and correspondence with the journal editor and its external reviewers. Overall, I led this paper from the initial formation of the idea to the publication, as the first author. AM and PW contributed by providing advice on the data analytics and development of the discussion section of the paper. AM, PW, and other co-authors reviewed the draft of this paper and provided comments to support the development of this article, for which I am grateful..

SECTION E

Student Signature	Leslie Edwards
Date	18 January 2024

Supervisor Signature	Ai Milojevic
Date	22 January 2024

Science of the Total Environment 772 (2021) 144836

Contents lists available
ScienceDirect
Science of the Total Environment

journal www.elsevier.com/locate/scitote

Personal exposure monitoring of $PM_{2.5}$ among US diplomats in Kathmandu during the COVID-19 lockdown, March to June 2020

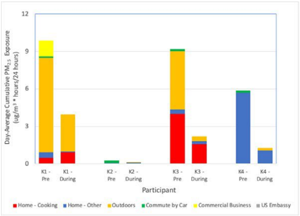
Leslie Edwards [a,*], Gemma Rutter [b], Leslie Iverson [b], Laura Wilson [c], Tandeep S. Chadha [d], Paul Wilkinson [a], Ai Milojevic [a]

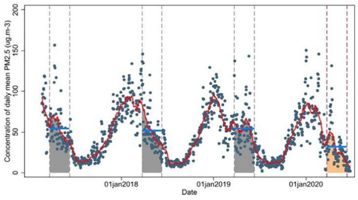
[a] London School of Hygiene and Tropical Medicine, London, England, United Kingdom [b] United States Embassy in Kathmandu, Nepal
[c] Johns Hopkins Bloomberg School of Public Health, Baltimore, MD, USA
[d] Applied Particle Technology, St. Louis, MO, USA

HIGHLIGHTS

- Ambient $PM_{2.5}$ in Kathmandu was approximately 40% lower during COVID19 lockdown in 2020 than in the same period of the previous three years
- Reduction in personal $PM_{2.5}$ exposure during the lockdown reflect altered activity patterns and lower $PM_{2.5}$ in selected microenvironments.
- Time spent outdoors and cooking at home were large contributors to personal exposure to $PM_{2.5}$ for some diplomats
- Exposure to $PM_{2.5}$ in indoor environments was generally very low due to apparent effectiveness of room air cleaners and sealing windows and doors.

GRAPHICAL ABSTRACT





Article Information

Article history:
Received 14 August 2020
Received in revised form 14 December 2020
Accepted 23 December 2020
Available online 2 February 2021

Editor: Philip K. Hopke

Keywords:
Air quality
$PM_{2.5}$
Personal monitoring
COVID lockdown
Mitigation
Room air cleaners
Kathmandu

Abstract

The 2019 Novel Coronavirus SARS-CoV 2 (COVID-19[1]) pandemic has severely impacted global health, safety, economic development, and diplomacy. The government of Nepal issued a lockdown order in the Kathmandu Valley for 80 days from 24 March to 11 June 2020. This paper reports associated changes in ambient $PM_{2.5}$ measured at fixed-site monitors and changes in personal exposure to $PM_{2.5}$ monitored by APT Minima by four American diplomats who completed monitoring before and during lockdown (24 h for each period per person, 192 person hours in total). Time activities and use of home air pollution mitigation measures (use of room air cleaners (RACs), sealing of homes) were recorded by standardized diary. We compared $PM_{2.5}$ exposure level by microenvironment (home (cooking), home (other activities), at work, commuting, other outdoor environment) in terms of averaged $PM_{2.5}$ concentration and the contribution to cumulative personal exposure (the product of $PM_{2.5}$ concentration and time spent in each microenvironment). Ambient $PM_{2.5}$ measured at fixed-sites in the US Embassy and in Phora Durbar were 38.2% and 46.7% lower than during the corresponding period in 2017–2019. The mean concentration of $PM_{2.5}$ to which US diplomats were exposed was very much lower than the concentrations of ambient levels measured at fixed site monitors in the city both before and during lockdown. Within-person comparisons suggest personal $PM_{2.5}$ exposure was 50.0% to 76.7% lower during lockdown than before it. Time spent outdoors and cooking at home were large contributors to cumulative personal exposure. Low indoor levels of $PM_{2.5}$ were achieved at work and home through use of RACs and measures to seal homes against the ingress of polluted air from outside. Our observations indicate the potential reduction in exposure to $PM_{2.5}$ with large-scale changes to mainly fossil-fuel related emissions sources and through control of indoor environments and activity patterns.

---

[*] Corresponding author at: London School of Hygiene and Tropical Medicine, Keppel St, Bloomsbury, London WC1E 7HT, United Kingdom. E-mail address: leslie.edwards@lshtm.ac.uk (L. Edwards). 1 COVID-19: 2019 Novel Coronavirus SARS-CoV 2, $PM_{2.5}$: particulate matter with diameter smaller than 2.5 mg; BAM: Beta attenuation monitor, RAC: room air cleaner.

1. Introduction

The association between fine particulate matter smaller than 2.5 μm ($PM_{2.5}$) and multiple health conditions, including cardio-respiratory disease and premature mortality, is well-established (Cohen et al., 2017; J. J. Liu et al., 2019). An individual's personal exposure to $PM_{2.5}$ arises from the time and activity he/she spends in a multitude of different microenvironments throughout the day. COVID-19 restrictions are likely not only to have altered the concentrations of $PM_{2.5}$ and other pollutants in many such environments but also time-activity patterns. There have been many reports about improvements in air quality during COVID-19 restrictions in the US, China, Malaysia, Europe and elsewhere (Berman & Ebisu, 2020; Chen et al., 2020; Giani et al., 2020; Kanniah et al., 2020; Kumari & Toshniwal, 2020). In this paper we report on changes in outdoor $PM_{2.5}$ in Kathmandu, Nepal, as well as personal exposures of four diplomats who remained in the city during a period of COVID-19 restrictions (a 'lockdown') from 24 March to 11 June 2020 imposed by the government of Nepal (United States Embassy in Nepal, 2020).

During the lockdown, schools, all non-essential government, and private offices were ordered to close, and many activities were restricted or suspended (as described in Supplement Table A.1). Essential services that remained open included those relating to health care services, food stores, electricity supplies, fuel services, telephone services, transportation, and National defense offices. In accordance with local recommendations, the US Embassy in Kathmandu moved to limit personal activities to 'mission critical' only. Staff were advised to work from home where possible. Four of those staff recorded their personal exposure to $PM_{2.5}$ before and during the COVID-19 lockdown. It is the analysis of data from this monitoring as well of two fixed-site outdoor $PM_{2.5}$ monitors that we now report.

2. Materials and methods

2.1. Fixed site ambient air quality monitoring

Ambient $PM_{2.5}$ exposure level was measured by two Fixed Site Ambient Air Quality Monitoring stations (beta attenuation monitors, BAMs) supported by the US Embassy and located at: the Embassy grounds at Maharajhung Road in Chakrapath and the Phora Durbar Recreation Center for the Embassy staff in the Thamel neighborhood, approximately 3 miles (4.5 km) from the Embassy (Fig. A.1). The Thamel area has heavy road traffic while the US Embassy is located in an area of relatively low population density and vehicular traffic. Data monitoring at both sites began on February 21, 2017 and the $PM_{2.5}$ concentrations are reported as hourly averages of 15-minute sampling (United States Environmental Protection Agency, 2020). The monitoring equipment is maintained and calibrated by US Embassy staff in conjunction with the standard operating procedures of the US Environmental Protection Agency (EPA) for $PM_{2.5}$ monitoring (United States Environmental Protection Agency, 2023a). Data used in this study are publicly available at the Air Now website (https://www.airnow.gov/).

2.2. Personal exposure monitoring

In September 2019, we recruited US Embassy staff and family members in Kathmandu to a personal monitoring study of exposure to $PM_{2.5}$, with the intention to ask each participant to undertake monitoring for at least 48 h in each of four three-month periods ('seasons') over the following year. However, of the 30 original recruits, many left Kathmandu because of COVID-19. But four of those who remained completed a two day period of personal monitoring both before and during the lockdown (24 March to 11 June 2020) using an APT Minima personal exposure monitor equipped with optical particle counter technology (Applied Particle Technology, 2020; Li et al., 2020) (Fig. A.2). The sampling interval for this monitoring was set at 30 s and the sampling volume to 0.1 l air/ min. The APT Minima reports $PM_{2.5}$, PM_{10}, PM_1, number concentration in 6 size bins (0.3 to >10 μm), as well as temperature, humidity, and GPS coordinates for each sampling interval. Periods of monitoring with >30% missing data were excluded from the analysis. Each participant recorded time-activity patterns for the periods of monitoring using a standardized diary which records time, location, activity, and behavior including cooking, commuting, outdoor exercise and the use of RACs. They also completed a questionnaire about efforts to seal the home against the outdoor air and sources of air pollution inside the home.

Two methods were used to check the validity and accuracy of the personal monitoring data:

(1) Periodic co-location of each of the APT Minima personal monitors next to the US Embassy's BAM for short periods of side-by-side monitoring. Between September 2019 and June 2020 such collocated monitoring was carried out on four occasions of at

least 1 h for each monitor. On each occasion, the mean difference between the BAM and Minima monitors was less than the manufacturer's threshold for recalibration.

(2) Permanent co-location of an APT Maxima stationary air quality monitor next to the US Embassy's beta attenuation monitor (BAM-120, MetOne) in Phora Durbar, to track the sensor calibration for local ambient aerosols (Li et al., 2020). The Maxima has the same monitoring technology as the Minima used for personal monitoring but is surrounded with a durable, weather resistant exterior case. Comparison of APT Maxima with the BAM data showed a regression slope of 0.98, R-value of 0.9429 (Fig. A.3).

The four study participants (referred as K1, K2, K3 and K4) who carried out personal monitoring lived within one mile (1.5 km) of the US Embassy (Fig. A.1). Demographic information and characteristics of the home, including RAC use and other indoor air pollution mitigation activities are included in Table A.2. Participants had six (K4) to eleven (K1) Blueair RACs in their home, with a mixture of Blueair 205 (small) and Blueair 605 (large) models (Table A.2). All participants kept their RACs turned on during the monitoring period. Three participants kept their RACs on the highest available setting ("high") while one participant (K3) kept their RACs on the "medium" setting. Participants K1 and K4 took extra measures to seal their home to limit the inward flow of ambient air pollution, either by adding caulk paste and tape to windows and using door snakes at the base of exterior doors (K1) or by sealing windows and unused exterior doors with plastic sheeting and tape (K4).

2.3. Room air cleaners (RACs)

All US Embassy diplomats and family members benefited from air purification both at the Embassy and at home. US Diplomats are provided with Blueair RACs for their homes, the number, and models of which are based on the number of people occupying the home, the size of the home, and the year the employee arrived in Nepal. Families could request additional RACs if they had children in the household, have health conditions exacerbated by air pollution or other concerns about indoor air quality in their home. Blueair RAC model 205 has a certified clean air delivery rate (CADR) of 180 cubic feet per minute with five air changes per hour and the Blue Air RAC model 605 has a CADR of 500 cubic feet per minute with five air changes per hour. American families are advised to change the filter in their RAC once every six months and filters are provided by the US Embassy. Families have the option of sealing their windows and doors with plastic and duct tape or with caulk paste in order to limit inward flow of air pollution.

2.4. Analysis

To assess the influence of the COVID-19 restrictions on ambient $PM_{2.5}$ concentration during the period of COVID-19 restrictions, daily and hourly mean concentrations were compared with that observed in the same period (i.e. 24 March to 11 June) of preceding three years, 2017 to 2019. The differences were tested using the Kruskal-Wallis test.

For personal monitoring, the assignment of microenvironments to $PM_{2.5}$ measurements were determined from the time-activity diary and APT Minima-recorded GPS location, when available. We used five microenvironment-activity categories: home (cooking), home (other activities), inside the US Embassy, commuting by car and other outdoor environment (including restaurants, hotels, or shops). The occupancy time and averaged $PM_{2.5}$ concentrations were computed by microenvironment using measurement recorded for whole day. The contribution of each microenvironment to cumulative personal exposure ($\mu g/m^3$*hours) was computed by the product of occupancy time and hourly $PM_{2.5}$ concentration.

The study was approved by the US Department of State's Human Subjects Protection Committee and by the London School of Hygiene and Tropical Medicine's Research Ethics Committee.

3. Results

3.1. Ambient $PM_{2.5}$

Ambient concentrations of $PM_{2.5}$ varied substantially across the year, both at the US Embassy monitoring site and at the Phora Durbar Complex, but levels were appreciably lower in the period of COVID-19 restrictions (24 March to 11 June 2020) compared with the corresponding period in each of the preceding three years (Fig. 1). At the Embassy location, the period mean was 32.6 $\mu g/m^3$ (SD 27.7 $\mu g/m^{-3}$) in 2020 compared with 53.1 $\mu g/m^3$ (SD 36.1 $\mu g/m^3$) for 2017–2019 ($p < 0.0001$, Kruskal-Wallis). This represents a reduction of 38.2%. The corresponding figures for Phora Durbar were 33.2 $\mu g/m^3$ (SD 21.6 $\mu g/m^3$) in 2020 vs 62.3 $\mu g/m^3$ (SD 18.8 $\mu g/m^3$) in 2017–2019; ($p < 0.0001$, Kruskal-Wallis), a 46.7% reduction. The distributions of ambient $PM_{2.5}$

concentrations monitored at the Embassy and at Phora Durbar are summarized by year in Supplement Table A.3. The diurnal variation in both locations was also altered in the period of full COVID-19 restrictions compared with the corresponding period of the previous three years. At the Embassy location, there was a relatively pronounced peak (from a lower baseline) between 7 and 10 am in 2020 but a smaller evening rise than seen in the previous years (Fig. 2). At the Phora Durbar Complex, the reduction in levels in 2020 was fairly consistent across the day.

3.2. Personal monitoring

In total, 22,821 $PM_{2.5}$ measurements were recorded in 196 person hours for the four study participants, including 11,406 measurements in 96 h recorded before the COVID-19 restrictions and 11,415 measurements recorded in 96 h during the period of restrictions.

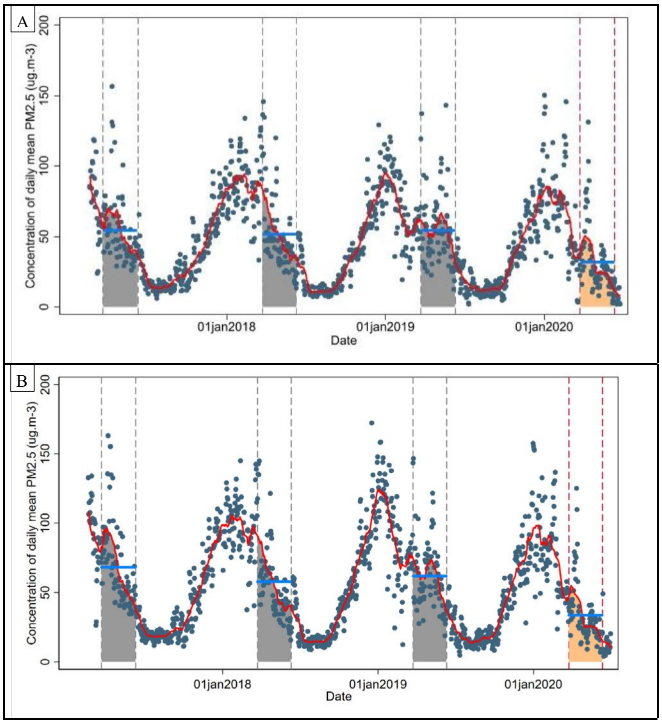


Fig. 1. Monitoring data for ambient $PM_{2.5}$ at [A] the US Embassy and [B] the Phora Durbar Recreational Complex, Kathmandu, 2017–2020. Blue dots represent daily means, the red line is the 31-day moving average and the vertical dashed lines and shading indicate 24 March to 11 June corresponding to the period of full COVID-19 restrictions in 2020. The blue bars represent the mean of the $PM_{2.5}$ concentrations in this period. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

During the lockdown, the mean $PM_{2.5}$ concentration for the period of monitoring for the four study participants ranged from 0.1 μg/m^3 (K2) to 3.8 μg/m^3 (K1) – Table 1. The percent change in personal exposure compared to pre-lockdown was −51% for K1, −50% for K2, −76% for K3 and −77% for K4. Corresponding ambient $PM_{2.5}$ monitoring data at the US Embassy monitoring site for the same days during lockdown ranged from 14.6 μg/m^3 (K3) to 22.0 μg/m^3 (K1). The changes in outdoor levels compared with pre-lockdown were: −46% for K1 days of monitoring, −63% for K2 days, −79% for K3 days and +11% for K4 days.

The time spent in various microenvironments was different during the period of lockdown compared to the period before lockdown (Fig. 3). During the period of full COVID-19 restrictions, all participants spent a majority of their monitored hours (range: 13 to 23.85 h) inside their home (Fig. 3). Consistent with advice, each participant spent less time at the Embassy (though K1 had no recorded time at the Embassy in either period). Both K3 and K4 worked in the Embassy during the lockdown but spent fewer hours there than they did before the lockdown. The proportion of time spent at home was higher for all four participants during the COVID-19 restrictions, but two participants, K1 and K4, spent slightly longer at non-commuting outdoor locations during the period of COVID-19 restrictions and the two who cooked at home, K1 and K3, cooked for slightly less time than before the lockdown.

It is difficult to compare concentrations of $PM_{2.5}$ in the different microenvironments directly because of the seasonality of outdoor concentrations. Personal monitoring levels at outdoor locations – commuting, commercial business locations and other outdoor locations – were all lower during the period of COVID-19 full restrictions and to an extent greater than the average reduction in the fixed site monitoring data (Fig. 4A). This may reflect differences in local sources of emissions in areas where people spend time as opposed to the change in ‘urban background’ at the fixed site monitors. However, there was an enormous range (0 μg/m^3 indoors at the US Embassy and at home when not cooking to 319 μg/m^3 at home while cooking) in the concentrations of $PM_{2.5}$ in different microenvironments at different times (Table 1).

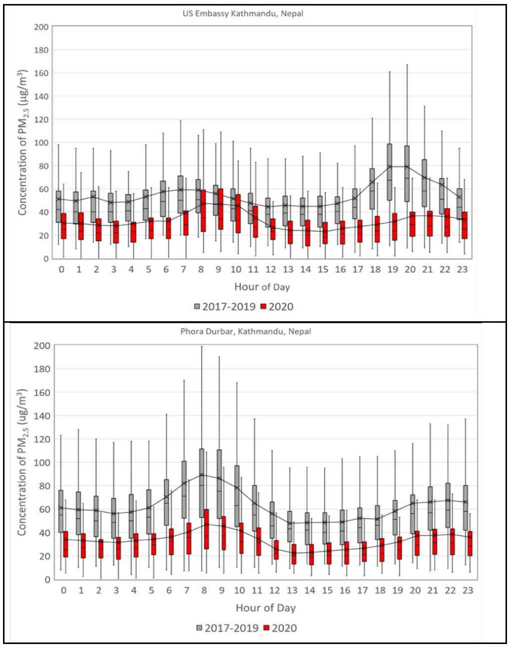


Fig. 2. Diurnal pattern of $PM_{2.5}$ concentrations including mean and interquartile ranges (IQR) at [A] the US Embassy and [B] the Phora Durbar Recreational Complex, Kathmandu, during the period of full COVID-19 restrictions in 2020 (24 March to 11 June, red) and corresponding dates in 2017–2019 (gray). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Participant K2 had the lowest mean $PM_{2.5}$ concentration at home, excluding time spent cooking – 0.1 μg/m³ both during and before lockdown. K2 sealed their windows and unused exterior doors with plastic sheeting and tape and had nine RACs in use in the home and the smallest size home among the 4 participants (1680 ft²).

K4 had the highest mean $PM_{2.5}$ in the home environment which reduced by from 11.4 μg/m³ prior to the lockdown to 1.5 μg/m³ during the lockdown, a decrease of 86%, compared to a decrease of only 11% in the ambient hourly $PM_{2.5}$ measured at the US Embassy. K4 sealed their home with plastic sheeting and tape in January 2020, prior to the COVID-19 lockdown.

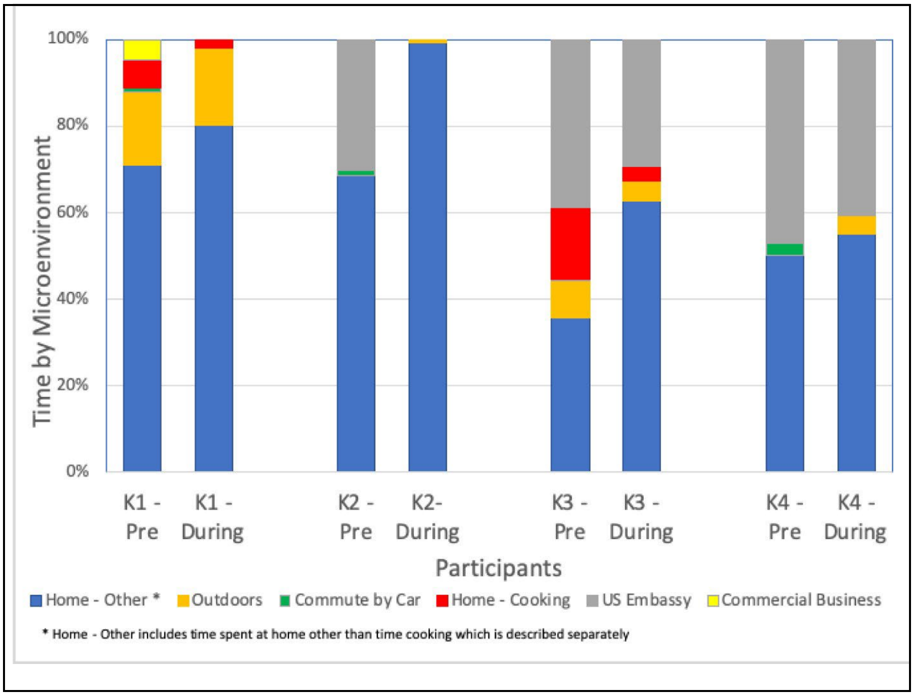
The indoor environments of the Embassy and at home for each participant except K4 had generally very low levels of $PM_{2.5}$ except during periods of cooking which generated ambient levels at home appreciably higher on average than in any outdoor environment, including while commuting.

The impact of these changes on day-average cumulative exposure is shown in Fig. 4B and Table A.4. All participants had lower day average cumulative $PM_{2.5}$ exposure during the COVID-19 restrictions which is attributable to spending less time outdoors and to reduced concentrations of $PM_{2.5}$ in the same environments (Table 2). Participant K2, who spent very little time outdoors and who had very low levels of $PM_{2.5}$ at both the Embassy and home environments, had very low levels of day average $PM_{2.5}$ exposure by comparison with other participants, all of whom had substantial exposure from periods outdoors in commuting and/or non-commuting activities or from relatively high levels in the home (participant K4). The differences in exposure on the basis of these selective days of monitoring was more than an order of magnitude between the least (K2) and most (K4) highly exposed individual both before and during the period of COVID-19 restrictions.

Personal monitoring tracings for participant K3 both before and during the COVID-19 lockdown are shown in Fig. 5. Participant K3 worked at the US Embassy and usually walked to work. During personal monitoring on 2 June 2020 (during COVID-19 restrictions), their mean hourly $PM_{2.5}$ concentration was 2.3 μg/m³, which was 84.2% lower than the mean hourly ambient $PM_{2.5}$ concentration measured at the US Embassy's fixed site monitor of 14.6 μg/m³ (Table 1). The tracing for this day, displayed in Fig. 5A, shows that cooking at home and walking to and from work contributed 76% and 24%, respectively, to their cumulative exposure for the day. This contrasts with pre-restriction measurements on 14 January 2020, when cooking at home, walking to and from work, and outdoor exercise contributed 32%, 57% and 11%, respectively, to the cumulative day total. In both of these monitoring sessions, participant K3 had nine RACs in their home including two Blueair 605 RACs and seven Blueair 205 RACs and they placed at least one RAC their living room, bedroom, and kitchen. Windows in their home were not sealed shut and they occasionally kept their front door ajar during the daytime.

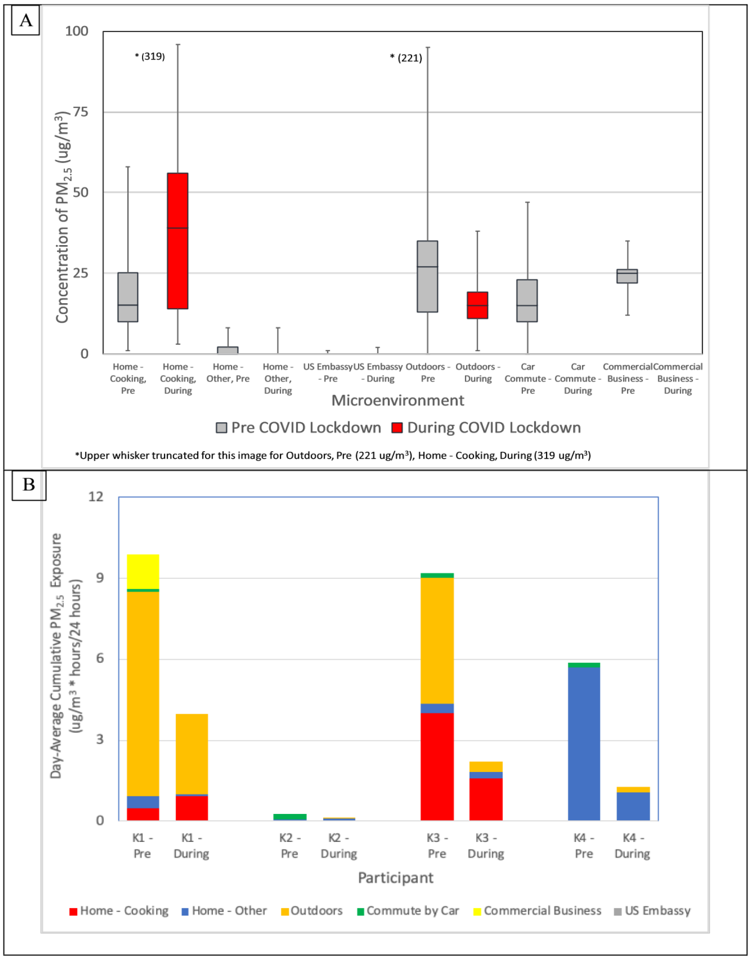
Table 1 Mean concentration of PM$_{2.5}$ by microenvironment for participants and daily mean PM$_{2.5}$ measured at fixed-site outdoor monitor for the corresponding days.

		Mean [PM$_{2}$] in µg/m^{3}											
		K1			K2			K3			K4		
		Restriction status		% change	Restriction status		% change	Restriction status		% change	Restriction status		% change
		Pre-	During		Pre-	During		Pre-	During		Pre-	During	
Day mean [PM$_{2.5}$] (IQR) at fixed-site monitor for days of personal monitoring		40.9 (34, 44)	22.0 (14, 27)	−46%	45.1 (37, 5	16.8 (14, 21)	−63%	70.9 (49, 92)	14.6 (8, 21)	−79%	15.8 (12, 20)	17.6	11%
Outdoor	Commuting	15.3 (14, 17)	NA	NA	18.8 (6, 26)	NA	NA	24.5 (2, 47)	NA	NA	6.2 (5, 7)	NA	NA
	Business	24.7 (23, 26)	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
	Other	24.1 (13, 33)	16.7 (13, 19)	−31%	NA	6.9 (6,8)	NA	56 (29, 79)	8.4 (3, 12)	−85%	NA	16.4 (12, 18)	NA
Indoor	Embassy	NA	NA	NA	0 (0,0)	NA	NA	0 (0, 1)	0 (0, 0)	0%	0 (0, 0)	0 (0,0)	0%
	Home – Cooking	11.2 (8, 15)	44.6 (10, 61)	298%	NA	NA	NA	26 (25, 32)	47.4 (13, 49)	82.3%	NA	NA	NA
	Home – Other	0.8 (0, 1)	0.1 (0, 0)	−88%	0.1 (0,0)	0.1 (0,0)	0%	0.9 (0, 1)	0.4 (0, 1)	−56%	11.4 (7, 15)	1.5 (0, 4)	−86%
Total		6.7 (0, 7)	3.8 (0, 0)	−51%	0.2 (0.0)	0.1 (0,0)	−50%	9.5 (0, 8)	2.3 (0, 0)	−76%	5.8 (1, 10)	1.0 (0, 2)	−83%



* Home - Other includes time spent at home other than time cooking which is described separately

Fig. 3. Comparison of time-activity patterns (time in specified microenvironments) before (pre) and during the period of full COVID-19 restrictions (24 March to 11 June 2020).



*Upper whisker truncated for this image for Outdoors, Pre (221 ug/m³), Home - Cooking, During (319 ug/m³)

Fig. 4. [A] Median, minimum, maximum, and interquartile range (IQR) concentrations of $PM_{2.5}$ by microenvironment and [B] contribution of each microenvironment to the day-average cumulative exposure computed as the product of $PM_{2.5}$ concentration and hours of exposure per day (µg/m^{-3}·h). Both graphs prepared using weekday (Monday-Friday) data measured before ("pre") and during the period of COVID-19 restrictions.

Table 2 Results of weekday personal monitoring: hours of exposure and mean cumulative exposure (product of time in environment x mean $PM_{2.5}$ concentration) by micro-environment for participants K1, K2, K3 and K4.

		Cumulative exposure (time x $[PM_{2.5}]$) in µg.m^{-3}.h (hours in microenvironment in brackets)											
		K1			K2			K3			K4		
		Restriction status		Change (hours)	Restriction status		Change (hours)	Restriction status		change (hours)	Restriction status		Change (hours)
		Pre- (hours)	During (hours)		Pre- (hours)	During (hours)		Pre- (hours)	During (hours)		Pre- (hours)	During (hours)	
Outdoor	Commuting	0.10 (0.2 h)	NA (0 h)	−0.10	0.22 (0.3 h)	NA (0 h)	−0.22	0.2 (0.2 h)	NA (0 h)	−0.2	0.18 (0.7 h)	NA (0 h)	−0.18
	Business	1.29 (1.3 h)	NA (0 h)	−1.29	NA (0 h)	NA (0 h)	0	NA (0 h)	NA (0 h)	0	NA (0 h)	NA (0 h)	0
	Other	7.56 (7.4 h)	2.96 (4.3 h)	−4.60	NA (0 h)	0.04 (0.15 h)	+0.04	4.67 (2 h)	0.39 (1.1 h)	−4.28	NA (0 h)	0.21 (1 h)	+0.21
Indoor	Embassy	NA (0 h)	NA (0 h)	0	0 (7.4 h)	NA (0 h)	0	0 (9.2 h)	0 (7 h)	0	0 (11.3 h)	0 (10h)	0
	Home – cooking	0.47 (1 h)	0.93 (0.5 h)	+0.46	NA (0 h)	NA (0 h)	0	4.01 (3.7 h)	1.58 (0.8 h)	2.43	NA (0 h)	NA (0 h)	0
	Home – other	0.47 (14.1 h)	0.08 (19.2 h)	−0.39	0.07 (16.3 h)	0.1 (23.85 h)	+0.03	0.33 (8.9 h)	0.25 (15.1 h)	−0.08	5.7 (12h)	1.08 (13h)	−4.62
Total		9.88	3.97	−5.91 (−59.8%)	0.29	0.14	−0.15 (−51.8%)	9.21	2.22	−7.0 (−75.9%)	5.88	1.29	−4.59 (78.1-%)

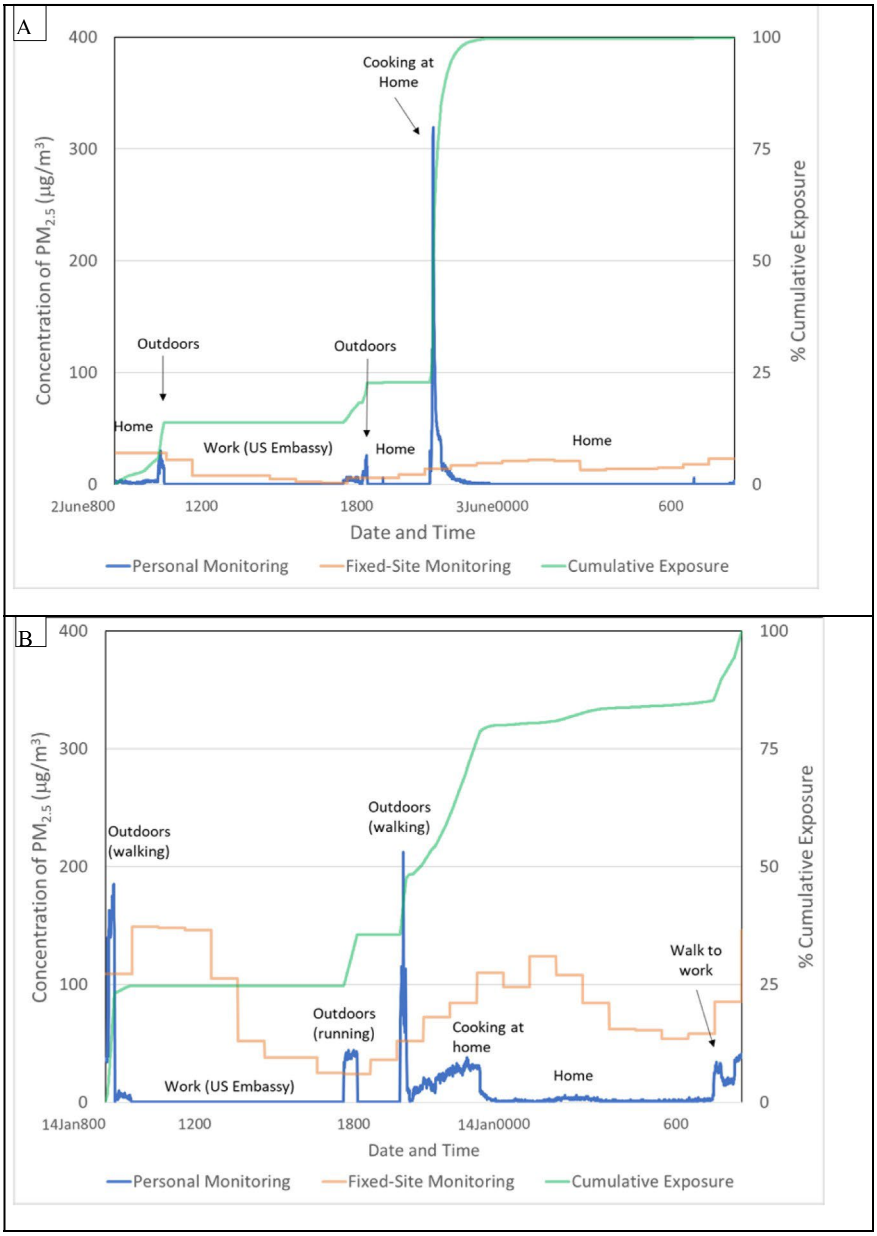


Fig. 5. [A] Personal exposure profile for participant and time activity pattern for an example day during and [B] before full COVID-19 restrictions. Data for volunteer K3.

4. Discussion

In this paper, we provide evidence of the impacts of activity restrictions during the COVID-19 pandemic on personal exposure to $PM_{2.5}$ of four US Embassy staff based in Kathmandu as well as changes in outdoor $PM_{2.5}$ concentrations. This evidence shows appreciable reductions in both outdoor $PM_{2.5}$ levels and in personal exposure, with the reduction in personal exposure being due to altered activity patterns as well as to the reduced concentrations in various microenvironments. It also provides important evidence about the apparent effectiveness of indoor air filtration combined with anti-infiltration home sealing measures in reducing $PM_{2.5}$ in the home environment.

Ambient concentrations of $PM_{2.5}$ from the fixed-site monitors at the US Embassy and in Phora Durbar were 38.2% and 46.7% lower during the period of full COVID-19 restrictions than in the corresponding period of the preceding three years. These changes in ambient levels are somewhat larger than those reported in a study of the change in air quality in 50 capital cities during the first month of lockdown (Rodriguez-Urrego & Rodriguez-Urrego, 2020) which reported a mean decrease of 12% in ambient $PM_{2.5}$ levels (though an increase in ambient $PM_{2.5}$ in Kathmandu). Our observed changes were more similar to those reported in a large-scale study using satellite-level data and more than 10,000 air quality stations which suggested that COVID-19 restrictions were associated with a 31% decrease in $PM_{2.5}$ (95% CI: 17–45%) (Venter et al., 2020) and with a study in New Delhi, India, which found a 39% decrease in $PM_{2.5}$ during the first six weeks of lockdown compared to the same period in 2019 (Mahato et al., 2020).

The reductions we observed for Kathmandu reflect the decrease in economic activity, traffic volumes and the temporary closure of selected industries, although traffic density and source apportionment data would be helpful to better understand the contribution of changes in specific emission sources. An important local source of particle pollution that remained operational during the lockdown was brick manufacturing (Anonymous, 2020; Eli, 2020) and emissions from this source as well as forest fires near Kathmandu may have contributed to the initially high levels of ambient $PM_{2.5}$ in April of that year (Gurung, 2020) before the subsequent decrease in ambient levels as precipitation increased.

Participants had mean concentrations of $PM_{2.5}$ that were 50.0% to 76.7% lower than their own mean hourly concentration prior to lockdown and 82.7% to 99.4% less than the mean hourly ambient $PM_{2.5}$ measured at the US Embassy's fixed site monitor. This low exposure compared with ambient levels reflects the fact that American Embassy staff spent much of their day in indoor environments (at home and at work) where $PM_{2.5}$ concentrations were very low because of the use of high quality RACs and, in some cases, the sealing of homes to the ingress of polluted air from outside by use of plastic sheeting, tape and caulking. Three of four participants reduced their time spent outdoors by 50% during the lockdown while the fourth participant increased their time outdoors by just 15 min. This reduction in time outdoors, decreased ambient $PM_{2.5}$ during the lockdown period compared to the monitoring period before COVID-19, and the reduction in indoor $PM_{2.5}$ were responsible for the decrease in personal exposure.

There are several limitations to the study, many of which directly relate to the restrictions of COVID-19: limited monitoring because of the return of many participants to the US and difficulty delivering equipment to participants homes during the lockdown; the absence of data on changes in specific emissions sources, including traffic volumes, that would be helpful in understanding the source contributions to changes in ambient levels; and the fact that we had measurements of only $PM_{2.5}$ concentrations and not of other pollutants or of indoor CO_2 levels. As homes were tightly sealed to reduce the indoor $PM_{2.5}$, there is potential that the concentration of other pollutants derived from indoor sources might increase but data are not available to inform conclusions about ventilation and indoor pollutant levels more generally. This is important because US Embassy staff spend much of their time indoors. While the air inside the US Embassy and many homes is highly filtered, this does not control all pollutants of potential concern to health. Additional studies with a greater number of participants are needed, including of Kathmandu residents who do not have the large number of RACs and other mitigation activities in place in their homes.

5. Conclusions

COVID-19 restrictions in Kathmandu were associated with substantial reductions in ambient concentrations of $PM_{2.5}$ and with large reductions in the personal exposure to $PM_{2.5}$ of US diplomats, due to both altered activity patterns (with less outdoor activity during lockdown) and lower $PM_{2.5}$ concentrations in many microenvironments. The mean concentration of $PM_{2.5}$ to which US diplomats are exposed is very much lower than the concentrations of ambient levels measured at fixed site monitors in the city, reflecting the high proportion of time they spend in indoor environments with low $PM_{2.5}$ concentrations due to use of room air cleaners and sealing of homes against the ingress of polluted air. However, cooking at home was a leading contributor to personal exposure to $PM_{2.5}$, along with time spent outdoors in commuting or at other locations. Our observations indicate the potential reduction in exposure to $PM_{2.5}$ with large-scale changes to mainly fossil-fuel emissions sources and through control of indoor environments and activity patterns.

Funding source

The US Embassy in Kathmandu, Nepal purchased the monitoring equipment used in the study. No other funding was obtained for the project.

CRediT authorship contribution statement

Leslie Edwards: Conceptualization, Writing – original draft, Data curation. Gemma Rutter: Project administration, Data curation. Leslie Iverson: Project administration, Writing – review & editing. Laura Wilson: Data curation. Tandeep S. Chadha: Software, Methodology, Writing – review & editing. Paul Wilkinson: Formal analysis, Supervision, Conceptualization. Ai Milojevic: Supervision, Conceptualization, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

We thank Ms. Durga Godar (U.S. Embassy in Nepal) for coordinating materials for the study, Mr. Todd Tiffany (U.S. Department of State) for support of the monitoring program, Mr. Grant Ludwig (U.S. Embassy in Nepal) and Mr. Adam Ludwig for assistance with intersensory variability testing, and Ms. Claire Huson and Dr. Wayne Quillin (U.S. Department of State) for encouragement to study the health effects of air pollution exposure.

Funding

This project was supported by the U.S. Department of State, Washington, DC and the U.S. Embassy in Kathmandu, Nepal.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2020.144836.

References

Anonymous. (2020, April 12, 2020). It's the Brick Kilns, Opinion. The Kathmandu Post. Retrieved from https://kathmandupost.com/editorial/2020/04/12/it-s-the-brick-kilns

Applied Particle Technology. (2020). Automated Environmental Health and Safety. Retrieved from https://appliedparticletechnology.com/

Berman, J. D., & Ebisu, K. (2020). Changes in U.S. air pollution during the COVID-19 pandemic. Science of the Total Environment, 739, 139864. doi:https://doi.org/10.1016/j. scitotenv.2020.139864.

Chen, K., Wang, M., Huang, C., Kinney, P.L., Anastas, P.T., 2020. Air pollution reduction and mortality benefit during the COVID-19 outbreak in China. The Lancet. Planetary Health 4 (6), e210–e212. https://doi.org/10.1016/S2542-5196(20)30107-8.

Cohen, A.J., Brauer, M., Burnett, R., Anderson, H.R., Frostad, J., Estep, K., ... Forouzanfar, M.H., 2017. Estimates and 25-year trends of the global burden of disease attributable to ambient air pollution: an analysis of data from the Global Burden of Diseases Study 2015. Lancet 389 (10082), 1907–1918. https://doi.org/10.1016/S0140-6736(17) 30505-6.

Eli, A.L., Baral, J., Saikawa, P., E., 2020. Dirty Stacks, High Stakes: An Overview of the Brick Sector in South Asia. Retrieved from http://documents1.worldbank.org/curated/en/685751588227715919/pdf/Dirty-Stacks-High-Stakes-An-Overview-of-Brick-Sectorin-South-Asia.pdf.

Giani, P., Castruccio, S., Anav, A., Howard, D., Hu, W., Crippa, P., 2020. Short-term and longterm health impacts of air pollution reductions from COVID-19 lockdowns in China and Europe: a modelling study. The Lancet. Planetary Health 4 (10), e474–e482. https://doi.org/10.1016/S2542-5196(20)30224-2.

Gurung, A., 2020. Forest Fire Rages on in Lamjung Community Forest. The Kathmandu Post. Retrieved from. https://kathmandupost.com/2/2020/04/09/forest-fire-rageson-in-lamjung-community-forest.

Kanniah, K.D., Kamarul Zaman, N.A.F., Kaskaoutis, D.G., Latif, M.T., 2020. COVID-19's impact on the atmospheric environment in the Southeast Asia region. Sci. Total Environ. 736, 139658. https://doi.org/10.1016/j.scitotenv.2020.139658.

Kumari, P., & Toshniwal, D. (2020). Impact of lockdown measures during COVID-19 on air quality - a case study of India. International Journal of Environmental Health

Research, 1–8. doi:https://doi.org/10.1080/09603123.2020.1778646.

Li, J., Mattewal, S.K., Patel, S., Biswas, P., 2020. Evaluation of nine low-cost-sensor-based particle matter monitors. Aerosol Air Qual. Res. 20, 254–270.

Liu, J. J., Wang, F., Liu, H., Wei, Y. B., Li, H., Yue, J., … Wang, J. (2019). Association of ambient fine particulate matter with increased emergency ambulance dispatches for psychiatric emergencies: a time-series analysis. The Lancet, 394 (Supplement 1), S7. doi: https://doi.org/10.1016/S0140-6736%2819%2932343-8.

Mahato, S., Pal, S., Ghosh, K.G., 2020. Effect of lockdown amid COVID-19 pandemic on air quality of the megacity Delhi, India. Sci. Total Environ. 730, 139086. https://doi.org/ 10.1016/j.scitotenv.2020.139086.

Rodriguez-Urrego, D., & Rodriguez-Urrego, L. (2020). Air quality during the COVID-19: PM2.5 analysis in the 50 most polluted capital cities in the world. Environmental Pollution, 266(Pt 1), 115042. doi:https://doi.org/10.1016/j.envpol.2020.115042.

United States Embassy in Nepal. (2020). COVID-19 Information Page. Retrieved from https://np.usembassy.gov/covid-19-information-2/

United States Environmental Protection Agency. (2020). AirNOW Department of State. Retrieved from https://www.airnow.gov/international/us-embassies-and-consulates/

Venter, Z.S., Aunan, K., Chowdhury, S., Lelieveld, J., 2020. COVID-19 lockdowns cause global air pollution declines. Proc. Natl. Acad. Sci. U. S. A. https://doi.org/10.1073/ pnas.2006853117.

4.3 Postscript to research paper

My contributions to this paper include (1) developing the original concept for this natural experiment following the imposition of the COVID-19 lockdown in Kathmandu in March 2020, (2) creating the data collection form that diplomats used to record their daily activities, use of air purifiers and demographic characteristics, (3) submitting the study to the London School of Hygiene and Tropical Medicine's Research Ethnics Committee for review, (4) submitting the study to the US Department of State's Human Subjects Protection Committee for review, (5) assembling the personal monitoring data from the study participants and ambient data into a database, (6) conducting interviews with diplomats to learn more about their daily activities, (7) conducting data cleaning and data maintenance for personal monitoring data, (8) conducting the data analysis for this project, (9) writing the first draft of the manuscript, (10) incorporating advice from co-authors into subsequent drafts of the manuscript, (11) preparing all tables and figures included in the manuscript, (12) submitting the manuscript and related materials to the journal *Science of the Total Environment* for consideration, and (13) updating the manuscript to reflect feedback from the journal's editors. Further details about my contributions to the research are available on the Research Paper Cover Sheet (Item D) included in Section 4.2 of my thesis.

The findings from this natural experiment provided evidence about the time diplomats' spent in various microenvironments including home (including time cooking at home), outdoors, commuting by car, and the US Embassy. My findings helped reinforce prior suspicions about the importance of air quality in the home, as study participants spent a majority of the time under observation in their home in Kathmandu. The study also helped to increase understanding about the $PM_{2.5}$ concentration in microenvironments and diplomat's use of air purifiers in their homes. This information was helpful in the development of the intervention study described in Chapter 5 and helped to inform the sensitivity analysis in the health modeling study in Chapter 6.

Figure 1 in the published article included ambient $PM_{2.5}$ data collected at fixed-site monitors at the US Embassy and at the Phora Durbar Recreational Complex in Kathmandu. The data in this figure was not adjusted for meteorological conditions such as temperature, wind, or precipitation.

4.4 Fulfillment of thesis objectives

The natural experiment study presented in this chapter fulfilled objective 2 and sub-objective 2a, as the published article detailed the quantification of the $PM_{2.5}$ exposure level for US diplomats and family members in a city with high ambient $PM_{2.5}$ by microenvironment and examined the relationship between the cumulative $PM_{2.5}$ personal exposure and the time spent in each microenvironment. The study revealed that COVID-19 restrictions in Kathmandu were associated with substantial reductions in ambient concentrations of $PM_{2.5}$ and large reductions in the $PM_{2.5}$ personal exposure among US diplomats, due to both altered activity patterns and lower $PM_{2.5}$ concentrations in many microenvironments. Cooking at home was a leading contributor to personal exposure to $PM_{2.5}$, along with time spent outdoors in commuting or at other locations. Study results indicated the potential reduction in exposure to $PM_{2.5}$ with large-scale changes to mainly fossil-fuel emissions sources and through control of indoor environments and activity patterns. The focus on $PM_{2.5}$ exposure in the home is a topic explored further in Chapter 5, shifting to examine how exposure may change following the implementation of high-capacity air purifiers in diplomats’ homes.

5 Ratio of $PM_{2.5}$ personal exposure to ambient $PM_{2.5}$: Intervention study of the enhanced mitigation measures at home

5.1 Introduction

This chapter of the results section includes a research paper that details an intervention study comparing the $PM_{2.5}$ personal exposure for US diplomats and adult members before and after the addition of high-capacity air purifiers in diplomats' residences in Kathmandu. Air purifiers are a key element of the US government's efforts to reduce $PM_{2.5}$ exposure for US diplomats working in highly polluted cities (Meredith, 2023; Wong, 2013b). The paper examines the relationship between $PM_{2.5}$ personal exposure and ambient $PM_{2.5}$ concentration in a variety of microenvironments including home (diplomatic residence), workplace, other indoor environments, commuting by car and outdoors. The purpose of the study was to understand the impact of added mitigation at home on the ratio of the personal $PM_{2.5}$ to ambient $PM_{2.5}$ (P/A) with the intention to use this information in concert with exposure-response functions and mortality statistics in the health model described in Chapter 6 of my thesis.

This study was originally proposed to be conducted for one year to examine seasonal trends in $PM_{2.5}$ personal exposure and changes in time spent in various microenvironments among US diplomats in Kathmandu. Unfortunately, more than half of the enrolled study participants in Kathmandu were evacuated back to the United States in March 2020 and ceased participation in the Kathmandu-based study. It was fortuitous that in late 2019 and early 2020, the US Embassy in Kathmandu began providing new, high-capacity air purifiers to US diplomats for use in their homes and I utilized the transition period of enhancing mitigation measures as the basis for this intervention study. The high-capacity air purifiers were provided in addition to the air purifiers provided to diplomats when they moved in Kathmandu. Among the 30 diplomats and family members enrolled in the study, 22 had at least one $PM_{2.5}$ personal monitoring session conducted before and after the new high-capacity air purifiers were implemented in diplomats' residences. When the personal monitoring study began in September 2019, I was not aware of the US Embassy's plan to distribute new high-capacity air purifiers to diplomats. I was able to conduct an intervention study among US diplomats and accompanying family members in Kathmandu to examine the impact of added mitigation in residences including high-capacity air purifiers and, in some cases, improved airtightness in homes. Outcomes in this study include the change in the ratio of the mean $PM_{2.5}$ concentration in study participants' homes to the $PM_{2.5}$ ambient concentration before and after adding increased mitigation in homes as well as the change in the P/A ratio.

This chapter addresses research objectives (2) conduct repeated personal $PM_{2.5}$ exposure monitoring sessions for 48 hours to characterize individual exposure profiles for US diplomats and family members living in a selected city with high ambient $PM_{2.5}$ and (2b) investigate whether the relationship between $PM_{2.5}$ personal exposure level and ambient $PM_{2.5}$ level changed after implementing enhanced mitigation measures at home (i.e. additional air purifiers and improvement of home air tightness) compared to that before implementation in the form of intervention study.

This activity is included as a research paper in chapter 5 and was accepted for publication in the journal *Environment Research: Health* in January 2023. The supplementary material from this paper is included in Appendix 3.

5.2 Research Paper

The cover sheet and research paper for this activity are included on subsequent pages. The published research paper has been transformed from an Adobe document to MS Word to optimize viewing in my thesis. The published research paper is also available on the following webpage https://iopscience.iop.org/article/10.1088/2752-5309/acb663 .

5.2.1 Research Paper Cover Sheet

London School of Hygiene & Tropical Medicine
Keppel Street, London WC1E 7HT

T: +44 (0)20 7299 4646
F: +44 (0)20 7299 4656
www.lshtm.ac.uk

RESEARCH PAPER COVER SHEET

Please note that a cover sheet must be completed <u>for each</u> research paper included within a thesis.

SECTION A – Student Details

Student ID Number	lsh1514008	**Title**	Ms.
First Name(s)	Leslie		
Surname/Family Name	Edwards		
Thesis Title	$PM_{2.5}$ Exposure and Associated Health Impacts on United States Government Diplomats and Accompanying Family Members With Multiple International Relocations: Exposure Measurement and Health Modeling Study		
Primary Supervisor	Dr. Ai Milojevic		

If the Research Paper has previously been published please complete Section B, if not please move to Section C.

SECTION B – Paper already published

Where was the work published?	Environmental Research: Health		
When was the work published?	1 March 2023		
If the work was published prior to registration for your research degree, give a brief rationale for its inclusion	Not Applicable		
Have you retained the copyright for the work?*	**No**	Was the work subject to academic peer review?	**Yes**

*If yes, please attach evidence of retention. If no, or if the work is being included in its published format, please attach evidence of permission from the copyright holder (publisher or other author) to include this work.

SECTION C – Prepared for publication, but not yet published

Where is the work intended to be published?	
Please list the paper's authors in the intended authorship order:	

Stage of publication	Choose an item.

SECTION D – Multi-authored work

For multi-authored work, give full details of your role in the research included in the paper and in the preparation of the paper. (Attach a further sheet if necessary)	My role and independent contributions to the research included planning the study, ensuring ethical approval, data collection and analytics and developing the manuscript from the original draft to the accepted version of the paper. Specifically, I led efforts to identify funding for the study including acquisition of personal monitors and a fixed site monitor used to ensure proper calibration for the personal monitors and travel funding. I developed a study protocol which included background and rationale for the study, data collection tools, a protocol to prepare personal monitors for each monitoring session, and instructions for personal monitoring data reporting to ensure timely transmission of data from the personal monitors to the cloud-based data storage platform. I applied and secured the ethic approval of the study both at LSHTM and at the US Department of State. I led the data curation for the study with input from my PhD supervisors Dr. Ai Milojevic (AM) and Dr. Paul Wilkinson (PW). This included development of the data collection tool used before every personal monitoring session, development of the data platform used to record questionnaire-based data, collaboration with experts who designed the personal monitoring tool to develop a protocol to obtain monitoring data and link that data with the questionnaire-based data such as demographics, use of air purifiers, and mode of transportation to and from work. I collaborated with US Embassy experts to collect details about study participants' housing structure and air purifiers used in the home. I led the data cleaning, management, and analysis with advice from supervisors, AM, and PW. I wrote the original draft of the manuscript including tables and figures, and led the edition based on comments from co-authors and feedback from journal editors and its external reviewers. Overall, I led this paper from the initial formation of the idea to the publication, as the first author. AM and PW contributed by providing advice on the data analysis and development of the discussion section

	of the paper. All co-authors reviewed the draft of this paper and provided comments to support the development of this article, for which I am grateful.

SECTION E

Student Signature	Leslie Edwards
Date	22 January 2024

Supervisor Signature	Ai Milojevic
Date	22 January 2024

IOP Publishing

ENVIRONMENTAL RESEARCH
HEALTH

PAPER

Impact of mitigation measures to improve home indoor air quality in Kathmandu, Nepal

RECEIVED
23 August 2022
REVISED
8 January 2023
ACCEPTED FOR PUBLICATION
26 January 2023
PUBLISHED
1 March 2023

Leslie Edwards[1,*], Paul Wilkinson[1], Gemma Rutter[2], Leslie Iverson[2] and Ai Milojevic[1]

[1] London School of Hygiene and Tropical Medicine, London, United Kingdom
[2] United States Embassy, Kathmandu, Nepal
[*] Author to whom any correspondence should be addressed.

E-mail: Leslie.Edwards@lshtm.ac.uk

Keywords: $PM_{2.5}$, indoors, outdoors, post-intervention, interventions, air purifiers

Abstract

Air purifiers (APs) and home sealing are interventions used to help protect U.S. diplomats against particle pollution in the home when working in polluted cities. We investigated the effect of these interventions on home indoor and personal $PM_{2.5}$ exposure in Kathmandu, Nepal. Twenty-one participants underwent repeated 48 hour personal monitoring before and after intervention. We analyzed these measurements by microenvironment. Indoor-outdoor ratios (I/O) using the home indoor $PM_{2.5}$ values were calculated in order to assess the air filtration capacity at home in light of increasing outdoor $PM_{2.5}$ post-intervention. To quantify the effect of intervention on home indoor $PM_{2.5}$, we conducted a meta-analysis of the results of dwelling-by-dwelling regression of indoor-on-outdoor (I/O) $PM_{2.5}$ concentrations. On average, adding high-capacity APs and home sealing led to a 15% decrease in $PM_{2.5}$ measured at home, excluding cooking periods, with a mean (standard deviation) of 7.5 (6.4) $\mu g\ m^{-3}$ pre- to 6.4 (8.1) $\mu g\ m^{-3}$ post-intervention despite a 57% increase in outdoor $PM_{2.5}$, from 43.8 (30.8) $\mu g\ m^{-3}$ pre- to 68.9 (40.7) $\mu g\ m^{-3}$ post-intervention. Overall mean personal exposure fell by 36% from 15.2 (10.6) $\mu g\ m^{-3}$ to 9.8 (8.7) $\mu g\ m^{-3}$. I/O ratios decreased as outdoor $PM_{2.5}$ strata increased; when outdoor $PM_{2.5} < 25\ \mu g\ m^{-3}$ the I/O decreased from 0.38 pre- to 0.12 post-intervention and when outdoor $PM_{2.5}$ was 101–200 $\mu g\ m^{-3}$ the I/O decreased from 0.12 pre- to 0.07 post-intervention. The mean regression slope of indoor-on-outdoor $PM_{2.5}$ decreased from 0.13 (95% CI 0.09, 0.17) in pre-intervention dwellings to 0.07 (0.04, 0.10) post-intervention. I/O ratios showed a weak negative (not statistically significant) inverse association with air changes per hour at home. In the high pollution environment of Kathmandu, APs with home sealing provide substantial protection against ambient $PM_{2.5}$ in the home environment, including during periods when outdoor $PM_{2.5}$ concentration was above 100 $\mu g\ m^{-3}$.

Introduction

United States (U.S.) diplomats live in numerous locations across the globe during their career, some of which may have high levels of outdoor air pollution. Given the well-established evidence of the harmful health effects of exposure to particulate matter <2.5 μm aerodynamic diameter ($PM_{2.5}$) and other air pollutants, various mitigation measures are deployed to attempt to limit their exposure to polluted air (Cohen et al., 2017; Cromar et al., 2021; Wellenius et al., 2012). Those measures typically include the filtration of air in embassy offices and increasingly also the use of air purifiers (APs) and the sealing of the home to reduce the penetration of polluted outdoor air to the home environment. These measures directed at reducing home-indoor concentrations of $PM_{2.5}$ are important because of the proportion of the day typically spent in the home environment: the Human Activity Pattern Survey, for example, found that on average Americans spend 87% of their day indoors including 69% inside the home (Klepeis et al., 2001). In this paper, we report a study of the impact of APs and home sealing on particle air pollution exposure of diplomats in Kathmandu, Nepal, a city which, in 2019, had an ambient (outdoor) $PM_{2.5}$ annual mean (standard deviation (SD)) of

45.4 (15.6) μg/m^{3}, a value nine times higher than the World Health Organization(WHO) annual mean guideline of 5 μg m^{-3} outdoors (United States Environmental Protection Agency, 2023a; World Health Organization, 2021). In this city, most U.S. diplomats and their families live in traditional-style dwellings constructed of cement with wooden accents, which tend to have a fairly high air permeability (are ‘leaky’, especially around windows and doors), and so are affected by the ingress of polluted air from the outdoor environment.

In the autumn of 2019, U.S. diplomat families were offered high-capacity APs to improve the filtration of air in the home and many also chose to implement additional measures such as weather-stripping and caulking to reduce the leakiness of windows, doors, and other apertures of the dwelling fabric. We conducted repeated personal air pollution monitoring by diplomats who work at the U.S. Embassy and diplomats’ adult family members who do not work at the Embassy to assess the effect of such measures on $PM_{2.5}$ at home and 24 hour personal $PM_{2.5}$ exposure.

1. Materials and methods

2.1 Study participants

The study was of 30 Americans affiliated with the U.S. Embassy in Kathmandu, however, results are reported only for the 21 Americans that added APs to their home (figure A1). Work status among the 21 participants include 11 US diplomats who worked at the Embassy and ten adult family members of diplomats (two worked part-time at the Embassy and eight did not work at the Embassy). They included five married couples where only one member of the couple worked at the Embassy. Participants were recruited by email sent to all U.S. diplomats working at the Embassy and their family members encouraging, but not requiring, participation. A survey was administered at the end of each monitoring session that included questions about APs use by room of the home, home sealing efforts, and method(s) of transportation used during the monitoring session.

2.2 Home air pollution mitigation

The homes occupied by participants, mostly traditional in style, were not insulated, the windows had either an aluminum/metal or a wooden frame and most were considered to be poorly sealed against the outdoor air. A photograph of a home similar to that occupied by study participants is included in figure A2. The heating, ventilation and air conditioning systems in participants’ homes included several electrically powered, wall mounted mini-split unit air conditioners with heat pumps and many homes had cooking fans in the kitchen and ventilation fans in the bathrooms. Study participants had access to electric oil-filled space heaters to use at home if needed.

Beginning in November 2019, all U.S. Embassy diplomats in Kathmandu, including the study participants who enrolled this study, were offered additional supply of high capacity APs (Blueair 605 APs, with a clean air delivery rate (CADR) of 500 feet^{3}/hour, converted to 14.2 m^{3}/hr) (Blueair, 2022b) and various measures to seal their home against the ingress of outdoor air including the use of caulking, draught-stripping and plastic sheeting on doors and windows. Twenty participants received two high-capacity APs while one participant received one high capacity AP. The intervention examined in this study is the addition of high capacity APs.

Before this intervention, study participants had an average of 7 (range: 2–10) low-capacity APs (Blueair 203 APs with CADR of 180 feet^{3}/hour, converted to 5.1 m^{3}/hr on average) (Blueair, 2022a) used to varying degrees (table 1). In order to consider the impact of the varied number of APs in use and the CADR for each house, home air purifier capacity (HAPC) (m/hour) was quantified by using the total of the CADR (m^3/hour) for each AP in use in each home divided by the surface area of the home (m^2).

Pre-intervention the total HAPC per hour in participants' homes ranged from 1.6 to 5.9. All of the study participants kept the low-capacity APs in their home after adding the high-capacity APs instead of replacing them. Information about the frequency of APs use and intensity setting (high, medium or low) used both pre- and post-intervention are summarized on table 1.

2.3 Monitoring of personal exposure

Study participants underwent two to three cycles of 48-hour personal monitoring for $PM_{2.5}$ between September 2019 and March 2020. Periods of monitoring before the introduction of the high-capacity APs and home sealing are referred to as 'pre-intervention' period, and those conducted after installation/home sealing as 'post-intervention' period. In total, 21 participants underwent personal monitoring in both pre-intervention and post-intervention periods, and the main results presented below are based on this group of 21 with paired measurement periods. Nine further study participants had monitoring from either the pre-intervention or the post-intervention period but not both.

Table 1. Characteristics of the 21 participants with paired personal monitoring data for the pre- and post-intervention periods.

Characteristic	Pre-Intervention	Post-Intervention
Gender *n (%)*		
Female	13 (62%)	
Male	8 (38%)	
Age group *n (%)*		
30–39	3 (14%)	
40–49	9 (43%)	
50–59	6 (29%)	
60–69	3 (14%)	
Worked at US Embassy *n (%)*		
Full time	11 (52%)	
Part time	2 (10%)	
Did not work at the Embassy[a]	8 (38%)	
Home size *(m^b)*		
mean (min-max)	266.3 (131.3–360.7)	
Main mode of transportation[b] *n (%)*		
Personal car	14 (67%)	13 (62%)
Walk or run	11 (52%)	9 (43%)
Bicycle	2 (10%)	2 (10%)
Taxi	0 (0%)	2 (10%)
Did not answer	2 (10%)	3 (14%)
Number of air purifiers (APs) at home[c] *mean (min-max)*		
Low capacity APs	6.8 (2–10)	6.8 (2–10)
High capacity Aps	0	1.9 (1–2)
Total home air purifier capacity (HAPC)[d] per hour *(m/hour), mean (SD)*	3.2 (1.2)	5.4 (1.9)
Efforts to seal the home *n (%)*		
Sealed, total	4 (19%)	11 (52%)
Sealed windows with tape and plastic	2 (9%)	3 (14%)
Sealed windows with tape	1 (5%)	3 (14%)
Sealed windows with caulk	0	2 (10%)
Sealed windows, backdoor with tape	0	1 (5%)
Sealing details unspecified	1 (5%)	2 (10%)
Not sealed	17 (81%)	10 (48%)
Always use APs in rooms at home *n (%)*		
Living Room	18 (86%)	21 (100%)
Bedroom	19 (90%)	20 (95%)
Kitchen	7 (33%)	12 (57%)
Setting used on APs *n (%)*		
Highest	13 (61%)	12 (57%)
Middle	4 (19%)	3 (14%)
Lowest	0	1 (5%)
Combination of Highest and Middle settings	2 (10%)	3 (14%)
Not answered	2 (10%)	2 (10%)
Leaky windows and doors in home *n (%)*		
Yes	15 (71%)	15 (71%)
No	0	0
Not answered	6 (29%)	6 (29%)

[a] Family member of diplomats that do not work at the Embassy.

[b] Participants could choose more than one mode of transportation. Pre-intervention 7 participants listed both walking and personal car. Post-intervention 5 participants listed walking and personal car and 1 participant listed taxi and personal car.

[c] Low capacity air purifiers (APs) have a clean air delivery rate (CADR) of 5.1 m^3/hour and high capacity APs have a CADR of 14.2 m^3/hour.

[d] Total home air purifier capacity (HAPC) (meters/hour) is the sum of the home air purifiers' clean air deliver rate (CADR) in cubic meters (m^3) per hour divided by the surface area of the home (m^2).

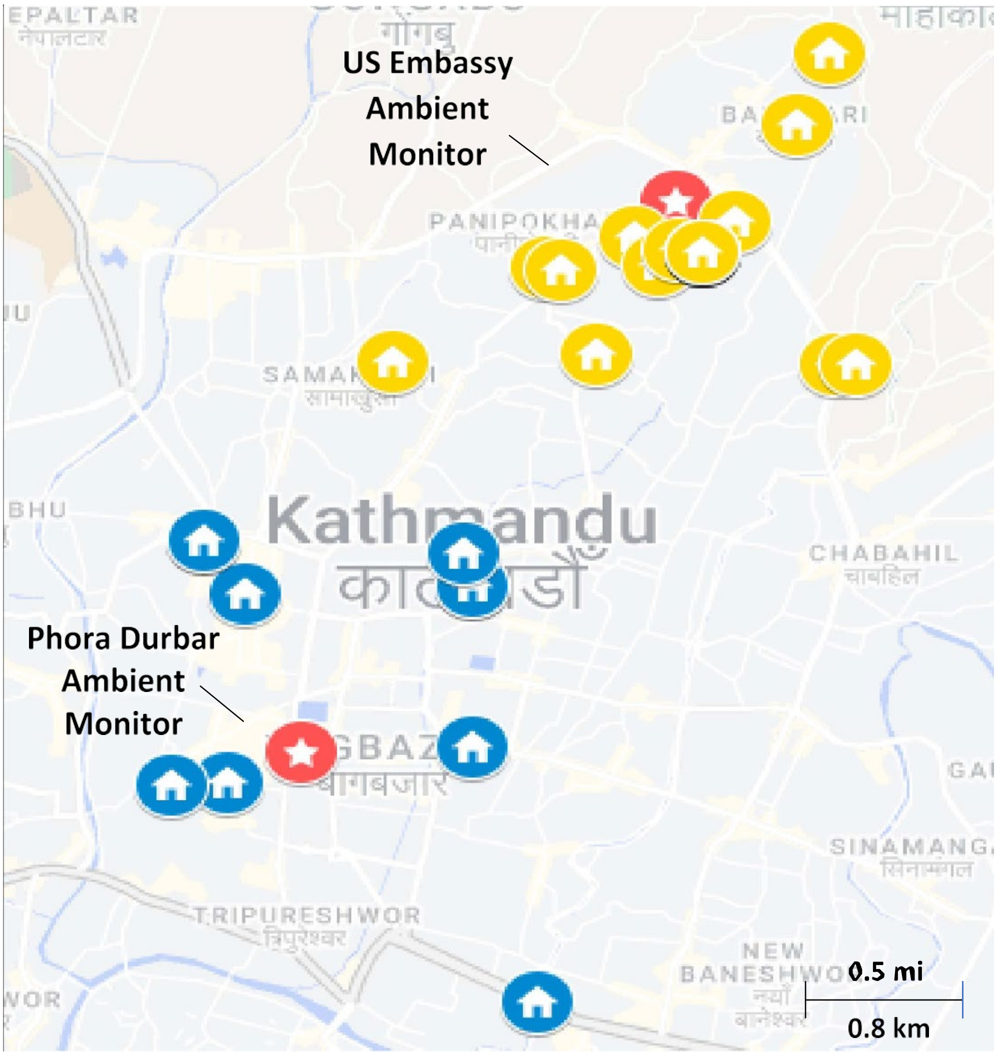


Figure 1. Map of ambient monitoring stations at the US Embassy and Phora Durbar Complex and homes of 21 study participants. Red markers indicate the fixed site ambient monitors located at the US Embassy and at the Phora Durbar Recreational Complex. Yellow icons are for the homes of the 13 participants that live closer to the ambient monitor located at the US Embassy. Blue icons are for the homes of the 8 participants that live closer to the ambient monitor located at the Phora Durbar Recreational Complex.

Participants wore an Applied Particle Technology (*APT) Minima* optical personal exposure monitor (figure A3) with a sampling interval of 1 min and sampling volume to 0.1 l air per minute (Applied Particle Technology, 2020; Li, 2020). Participants wore the personal monitor in a custom made crossbody carrying case with openings in the fabric for the personal monitor’s air collection outlet and charging port. Participants typically wore the crossbody carrying case with the personal monitor at waist level. No additional sampling tubing was needed for this personal monitor. The *APT Minima* records $PM_{2.5}$, temperature, and humidity for each sampling interval. Each participant recorded time-activity patterns for the periods of monitoring using a standardized diary. They were asked to record time and location of activities such as home cooking, commuting and other outdoor movements. They also completed a questionnaire about efforts to seal the home against the outdoor air, AP use and sources of air pollution inside the home during each monitoring session.

Ambient (outdoor) $PM_{2.5}$ was measured at two U.S. Embassy fixed site outdoor air quality monitoring stations (BAM-1020, MetOne beta attenuation monitors, (BAMs)) located at the Embassy grounds at Maharajhung Road in Chakrapath and the Phora Durbar Recreation Center in the Thamel neighborhood (figure 1). All homes were within 1.8 miles (2.9 kilometers) of an outdoor fixed-site air quality monitor. The Thamel area has heavy road traffic while the U.S. Embassy is located in an area of relatively low population density and vehicular traffic. $PM_{2.5}$ data from the outdoor monitor located closer to each participant's home was used in the analysis. The monitoring equipment is maintained and calibrated by U.S. Embassy staff in conjunction with the standard operating procedures of the U.S. Environmental Protection Agency (EPA) for $PM_{2.5}$ monitoring. $PM_{2.5}$ concentrations are reported as hourly averages of 15-minute sampling and are publicly available at the Air Now website (United States Environmental Protection Agency, 2023a).

An APT Maxima stationary air quality monitor was located next to the U.S. Embassy's BAM in Phora Durbar, to track the sensor calibration for local ambient aerosols. The Maxima has the same monitoring technology as the *Minima* used for personal monitoring but is surrounded with a durable, weather resistant exterior case. Comparison of APT Maxima in Phora Durbar with the BAM data showed a regression slope of 0.98, *R*-value of 0.9429. Independent of this study, a sensor performance evaluation conducted by South Coast Air Quality Management District which demonstrated a high level of agreement (R^2 = 0.86–0.91) when the APT Minima was run side-by-side with federal equivalent method instruments (South Coast Air Quality Monitoring District, 2020).

2.4 Data analysis

The microenvironments occupied by each participant throughout the period of monitoring were determined using data from the time-activity diary in combination with inspection of the $PM_{2.5}$ trace, and the temperature recorded by the personal monitor and outdoor temperature in an attempt to help improve the timing of the transition between environments. Six categories of microenvironment-activity were used in the study: (a) home (indoors, excluding cooking), (b) cooking at home, (c) inside the U.S. Embassy, (d) inside other indoor environments, including restaurants, hotels, and shops, (e) travel by car and (f) outdoors.

Participants did not reliably record periods of home cooking, so we labelled a period as a cooking period when the participant was in their home environment at a meal-time (7–9 am for breakfast, 12–2 pm for lunch, 5–8 pm for evening meal) and there was a sharp rise in $PM_{2.5}$ concentrations (see, for example, figure 3). Meteorological data including the daily ambient temperature and rainfall were examined and values were compared during pre- and post-intervention.

The database of personal exposure monitoring measurements recorded in this study was updated to include the corresponding hourly mean of the fixed-site ambient $PM_{2.5}$ monitor closest to each study participants' home for each personal monitoring datapoint recorded. This allowed for a comparison of the personal $PM_{2.5}$ to ambient $PM_{2.5}$ concentrations reflecting the direct timing of each personal monitoring session. Pre- and post-intervention mean (SD) and median (IQR) values for each microenvironment were calculated and the differences in means were tested using the Kruskal-Wallace test. The contribution of each microenvironment to cumulative personal exposure (hours $\times \mu g/m^3$) was computed as the product of number of hours within each microenvironment and the corresponding measured $PM_{2.5}$ concentration. The home indoor/outdoor (I/O) ratios of $PM_{2.5}$ concentrations were derived by dwelling-specific regression of the hourly mean personal monitoring $PM_{2.5}$ when the participant was at home (excluding periods of cooking) on the corresponding hourly outdoor $PM_{2.5}$ at the closer fixed monitoring site. The slopes of these regression analyses reflect the dwelling specific I/O ratio of $PM_{2.5}$ concentrations allowing for differences in outdoor $PM_{2.5}$ concentrations at the time of personal measurement at home. Dwelling-specific I/O ratios of $PM_{2.5}$ concentration were weighted by the number of observations to derive these I/O ratios, with results for study participants (or dwellings) having larger weights if they spent more hours at home during the pre- or post- intervention monitoring period.

Separate regression slopes and *y*-intercepts of indoor-on-outdoor $PM_{2.5}$ were obtained for pre- and post-intervention periods. Meta-regression of the dwelling-specific regression slopes and *y*-intercepts was subsequently performed to obtain summary measures before and after intervention. We also analyzed the general relationship between the I/O slopes and the capacity of the APs.

Sensitivity analyses of the I/O ratios included: (a) restricting analysis to times when the outdoor temperature was less than 18 °C (64.4 °F) (to attempt to remove the effect of window opening on warmer days), (b) restricting the analysis to the include monitoring sessions from the 18 participants with at least 8 h of personal monitoring conducted in the home per 48 h monitoring session both pre- and post-intervention, (c) restricting analysis to include only the monitoring sessions with high and/or middle AP settings, and (d) using data from all 30 study participants even if there was no paired data for both the pre- and post-intervention periods.

All analyses were carried out in Stata version 17.0 (StataCorp., 2022). The study was approved by the U.S. Department of State's Human Subjects Protection Committee and by the London School of Hygiene and Tropical Medicine's Research Ethics Committee.

3. Results

3.1 Characteristics of study participants

The primary analyses presented in the Tables and Figures below are based on the 21 participants that had paired measurements for both pre-intervention and post-intervention periods (table 1). Results for nine

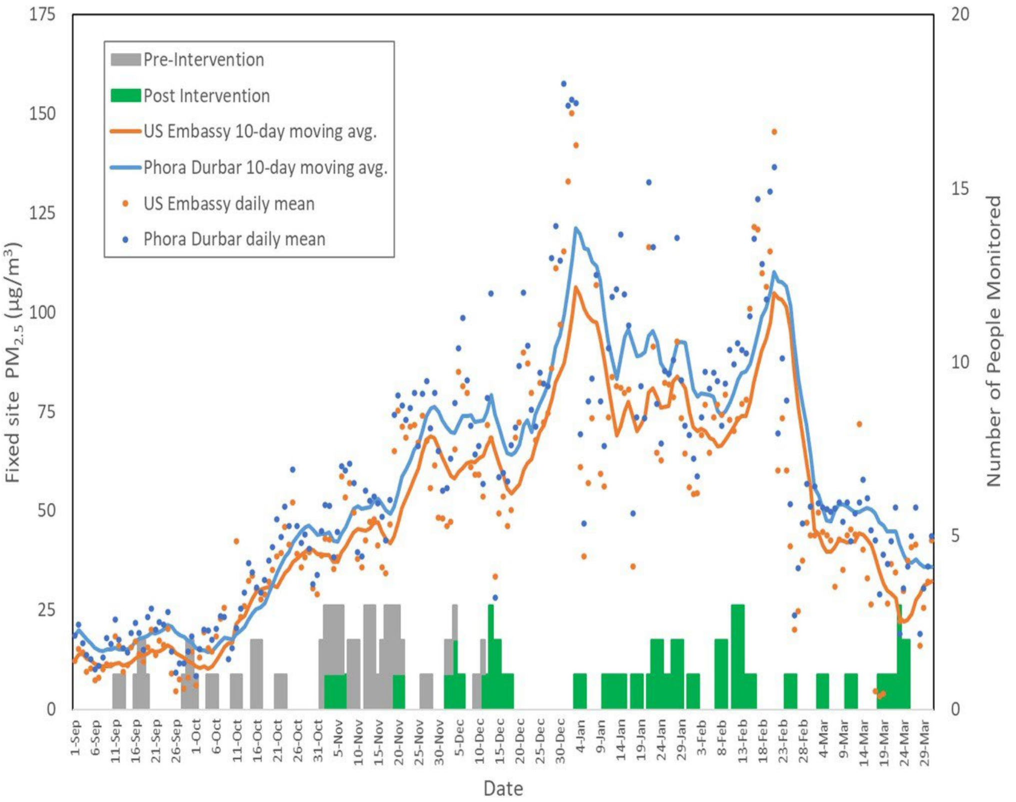


Figure 2. Monitoring data for ambient PM2.5 at the US Embassy and the Phora Durbar Recreational Complex, Kathmandu, September 2019 to March 2020. Measurements at the US Embassy fixed-site monitoring station are shown by orange dots (daily mean) and line (10-day moving average), those at Phora Durbar fixed-site monitoring station in blue dots and line; the vertical bars indicate the number of people with personal monitoring (grey for pre-intervention and green for post-intervention).

participants without paired measurements are included in one of the sensitivity analyses of the intervention effect in figure A5.

Among the 21 with paired measurements, 11 (52%) worked full-time at the U.S. Embassy, two (10%) worked part-time at the Embassy, and eight (38%) were family members of diplomats who lived in a dwelling designated for a diplomatic family but did not work at the Embassy. None were smokers nor did they live with anyone who smoked. Dwellings varied greatly in size from 131.3 m^2 to 360.7 m^2. Seven (33%) participants improved the home sealing during the study including one that sealed their windows using plastic sheeting and weatherproofing tape, two that sealed their windows with weatherproofing tape, two that sealed their windows with caulk, one that sealed their windows and backdoor with weatherproofing tape and one that did not specify how they improved their home seal (table 1). Adding high-capacity APs helped to increase the HAPC per hour in homes from mean (SD) of 3.2 (1.2) pre-intervention to 5.4 (1.9) post-intervention (table 1).

3.2 Ambient air quality and meteorological conditions

The hourly ambient $PM_{2.5}$ mean (SD) recorded at the closest fixed-site monitor increased from 45.3 (23.9) $\mu g/m^3$ pre- to 62.5 (32.1) $\mu g/m^3$ post-intervention (figure 2). The mean (SD) daily temperature and daily rainfall decreased from 15.8 (3.9)$^\circ$C and 4.8 (9.7) mm pre- to

12.0 (4.5) °C and 3.4 (6.2) mm post-intervention. The mean (SD) daily windspeed increased from 3.0 (0.4) km hour^{-1} pre- to 3.4 (0.7) km/hour post-intervention.

3.3 Reported change in behaviors and experience

In addition to the greater clean air delivery capacity, the reported use of APs in the living room, bedroom and kitchen increased following the intervention (table 1). During each personal monitoring session, participants were asked if they had leaky (draughty) windows and doorways at home. Even though seven participants improved the sealing of their home against outdoor air, the same number of people (15) reported having a leaky home pre- and post-intervention (six of the 21 participants did not answer this question).

3.4 Personal exposure by microenvironment

Table 2 shows summary statistics of personal monitoring $PM_{2.5}$by micro-environment, the corresponding concentrations of ambient $PM_{2.5}$, and time spent in each microenvironment before and after the intervention. The $PM_{2.5}$ mean (SD) at home, excluding periods of cooking, decreased from 7.5 (6.4) μg/m^3 pre- to 6.4 (8.1) μg/m^3 post-intervention (p = 0.26, Kruskal–Wallis) while the corresponding ambient $PM_{2.5}$ recorded at the closest fixed-site monitor while participants were at home increased from 41.8 (22.3) μg/m^3 pre- to 64.3 (26.4) μg/m^3 post-intervention (p = 0.01, Kruskal–Wallis). The ratio of the mean personal $PM_{2.5}$ at home (indoor) compared to the fixed-site ambient (outdoor) $PM_{2.5}$ was cut nearly in half from pre- (0.18) to post-intervention (0.10). The overall, time-averaged personal exposure to $PM_{2.5}$ across all micro-environments decreased from 15.2 (10.6) μg/m^3 pre- to 9.8 (8.7) μg/m^3 post-intervention (p = 0.19, Kruskal–Wallis), and the ratio of the mean personal $PM_{2.5}$ to the corresponding fixed-site ambient $PM_{2.5}$ concentration decreased from 0.32 pre-intervention to 0.16 post-intervention.

Table 2. Summary of $PM_{2.5}$ exposure by microenvironment, confined to 21 participants with both pre- and post-intervention measures.

Pre-Intervention, 21 monitoring sessions

1

	Microenvironment							
	Home—Indoors[a]	Home—Cooking	Indoor Other	Embassy	Commute by Car	Outdoors	Missing	Overall
$PM_{2.5}$ Mean (SD), $\mu g/m^3$	7.5 (6.4)	42.9 (36.0)	43.4 (61.6)	0.6 (0.6)	22.5 (11.0)	44.4 (27.0)	n/a	15.2 (10.6)
$PM_{2.5}$ Median (IQR), $\mu g/m^3$	5.4 (3.4, 10.8)	29.5 (22.2, 38.7)	28.5 (11.3, 48.5)	0.8 (0, 1.0)	21.8 (14.5, 30.2)	39.7 (28.9, 47.3)	n/a	5.1 (1.3, 17.6)
Fixed-Site Ambient[b] $PM_{2.5}$ mean (SD), $\mu g/m^3$	41.8 (22.3)	57.8 (27.6)	38.9 (19.7)	54.2 (23.7)	41.4 (21.9)	45.8 (26.4)	42.7 (21.6)	43.8 (30.8)
# Participants in this Microenvironment	21	13	19	11	16	21	19	21
% Time in Location	44%	2%	10%	12%	4%	5%	23%	100%
Time in Microenv[c], hrs	439.2 h	23.7 h	100.6 h	116.3 h	41.1 h	45.7 h	241.4 h	1008.0 h
Cumulative exposure (CE), $\mu g/m^{c*}$ hrs	3223.9	953.9	4355.2	86.8	911.3	1875.9	n/a	11 407.1
CE per participant, $\mu g/m^{c*}$ hrs	153.5	73.4	229.2	10.6	57.0	89.3	n/a	522.8
Personal/Ambient Ratio[d]	0.18	0.74	1.12	0.01	0.54	0.97	n/a	0.32

Post-Intervention, 21 monitoring sessions

	Home—Indoors[a]	Home—Cooking	Indoor Other	Embassy	Commute by Car	Outdoors	Missing	Overall
$PM_{2.5}$ Mean (SD), $\mu g/m^c$	6.4 (8.1)	58.5 (18.4)	38.3 (38.8)	0.2 (0.4)	23.3 (16.5)	38.0 (23.7)	n/a	9.8 (8.7)
$PM_{2.5}$ Median (IQR), $\mu g/m^c$	3.9 (1.4, 9.0)	50.3 (43.3, 75.5)	27.8 (17.7, 47.4)	0.0 (0.0,0.0)	21.4 (14.0, 26.8)	31.7 (19.7, 56.1)	n/a	2.6 (1.1, 12.0)
Fixed-Site Ambient[b] $PM_{2.5}$ Mean (SD), $\mu g/m^c$	64.3 (26.4)	85.9 (57.1)	61.9 (38.3)	48.2 (20.8)	69.0 (32.7)	58.1 (30.9)	67.3 (36.1)	68.9 (40.7)
# Participants in this Microenvironment	21	5	14	17	18	19	11	21
% Time in Location	61%	1%	8%	11%	3%	3%	13%	100%
Time in Microenv[c], hrs	613.8 h	7.6 h	77.8 h	110.1 h	30.4 h	33.2 h	135.1	1008.0 h
Cumulative exposure, $\mu g/m^{c*}$ hrs	3191.2	387.4	2021.6	5.8	737.5	1149.7	n/a	8100.9
CE per participant, $\mu g/m^{c*}$ hrs	152.0	18.4	96.3	0.3	35.1	54.7	n/a	367.7
Personal/Ambient Ratio[d]	0.10	0.68	0.62	<0.01	0.34	0.65	n/a	0.16

[a] Home—indoors category does not include periods of cooking which are separated and included under the heading 'home—cooking'.

[b] Ambient (outdoor) data derived from the fixed-site monitor that was closest to each participant's home, either the US Embassy Kathmandu or Phora Durbar monitor.

[c] Time in microenvironment is the total number of hours for all participants in this location during personal monitoring.

[d] Personal/Ambient ratio is the $PM_{2.5}$ mean divided by the fixed-site ambient $PM_{2.5}$ mean, calculated according to each microenvironment and collectively the pre- and post-intervention monitoring periods.

Table 3. Home indoor mean $PM_{2.5}$ concentration by strata of fixed-site outdoor $PM_{2.5}$ and the indoor/outdoor ratio among 21 participants with paired pre- and post-intervention personal monitoring. Analysis completed first using home excluding cooking periods and second with home including cooking periods.

Home Excluding Cooking Periods						
	Outdoor $PM_{2.5}$					
Pre-Intervention	*<25 $\mu g/m^3$*	*26–50 $\mu g/m^3$*	*51–75 $\mu g/m^3$*	*76–100 $\mu g/m^3$*	*101–200 $\mu g/m^3$*	*>200 $\mu g/m^3$*
Indoor (Home), mean ($\mu g/m^3$)	6.0	5.8	9.7	8.7	13.2	—
Outdoors, mean	15.9	38.9	61.3	84.4	105.7	—
Duration, hrs	127.1	177.2	81.1	37.2	6.2	—
Indoor/Outdoor Ratio	0.38	0.15	0.16	0.10	0.12	
Post-Intervention	*<25 $\mu g/m^3$*	*26–50 $\mu g/m^3$*	*51–75 $\mu g/m^3$*	*76–100 $\mu g/m^3$*	*101–200 $\mu g/m^3$*	*>200 $\mu g/m^3$*
Indoor (Home), mean ($\mu g/m^3$)	2.0	5.4	6.1	6.7	8.3	5.6
Outdoors, mean ($\mu g/m^3$)	16.5	41.0	62.1	84.4	123.6	242.3
Duration, hrs	75.7	165.7	163.4	97.4	88.3	4.4
Indoor/Outdoor Ratio	0.12	0.13	0.10	0.08	0.07	0.02
Home Including Cooking Periods						
	Outdoor $PM_{2.5}$					
Pre-Intervention	*<25 $\mu g/m^3$*	*26–50 $\mu g/m^3$*	*51–75 $\mu g/m^3$*	*76–100 $\mu g/m^3$*	*101–200 $\mu g/m^3$*	*>200 $\mu g/m^3$*
Indoor (Home & Cooking), mean ($\mu g/m^3$)	6.1	6.6	15.1	26.4	18.4	—
Outdoors, mean ($\mu g/m^3$)	16.0	39.0	60.8	84.7	105.8	—
Duration, hrs	128.4	191.5	90.4	44.6	8.8	—
Indoor/Outdoor Ratio	0.38	0.17	0.25	0.31	0.17	
Post-Intervention	<25 μ g/m^3	26–50 $\mu g/m^3$	51–75 $\mu g/m^3$	76–100 $\mu g/m^3$	101–200 $\mu g/m^3$	>200 $\mu g/m^3$
Indoor (Home & Cooking), mean ($\mu g/m^3$)	2.5	5.6	7.0	9.2	8.3	5.6
Outdoors, mean ($\mu g/m^3$)	16.6	41.2	62.6	84.8	122.6	242.3
Duration, hrs	75.9	166.3	175.3	105.2	95.0	4.4
Indoor/Outdoor Ratio	0.15	0.14	0.11	0.11	0.07	0.02

To examine the impact of the intervention on $PM_{2.5}$ concentrations inside the home including spikes generated during cooking periods, we analyzed the combined data for home and home-cooking micro-environments, which showed that the mean (SD) $PM_{2.5}$ measured at home *including* periods of cooking was 9.1 (6.9) $\mu g/m^3$ pre-intervention and 6.8 (8.8) $\mu g/m^3$ post-intervention (p = 0.45, Kruskal–Wallis). The ratio of the personal $PM_{2.5}$ at home including cooking periods to fixed-site ambient $PM_{2.5}$ was reduced by 48% from 0.21 pre-intervention to 0.11 post-intervention. Participants spent 61% of their recorded time at home post-intervention compared with 44% pre-intervention (results for home environment including cooking periods at home, table 2). Participants spent 3% of their recorded time outdoors post-intervention compared with 5% pre-intervention. Three participants shifted from walking to work pre-intervention to commuting to work by car or taxi during post-intervention monitoring sessions.

Results by stratum of outdoor $PM_{2.5}$ concentrations confirm the pattern of lower ratios of indoor to outdoor $PM_{2.5}$ after intervention both for analyses based on data that excludes periods of cooking and based on data that includes periods of cooking (table 3). In each of the outdoor $PM_{2.5}$ strata examined, the post-intervention I/O ratio was less than the pre-intervention ratio, with the largest pre-post differences in ratio observed in the strata with the lowest outdoor concentration of $PM_{2.5}$ ($<25\ \mu g/m^3$). Home $PM_{2.5}$ mean values and I/O ratios were often higher when cooking periods were included in the analysis compared to the analysis excluding cooking periods. For example, when ambient $PM_{2.5} < 25\ \mu g/m^3$, the pre-intervention I/O ratio was 0.38 both when excluding home cooking periods and when including home cooking periods, whereas the corresponding post-intervention I/O ratios were 0.12 and 0.15. Data showing personal monitoring data for both pre- and post-intervention periods are shown in figure 3 for one participant whose intervention included both additional APs and home sealing. The periods in the indoor environment excluding cooking are shown as the red trace in 3(A) and (B), and those during home cooking as light blue. Regression of the home (indoor) $PM_{2.5}$ measurements on the corresponding outdoor fixed-monitored $PM_{2.5}$ concentrations, excluding periods of cooking, are shown in figure 3(C) separately for the pre- and post-intervention monitoring periods. For this participant, there was a substantial reduction in the regression slope post-intervention.

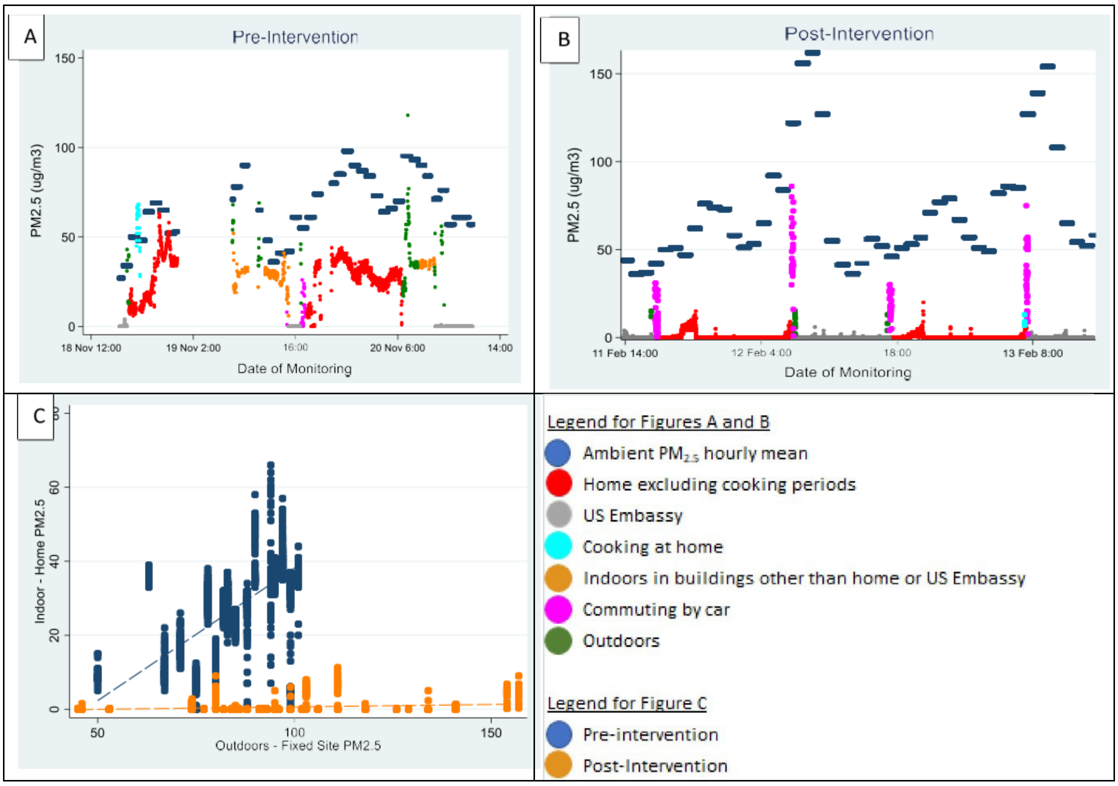


Figure 3. Personal exposure profile for a selected participant and time activity pattern before [A] and after [B] adding two additional room air cleaners and sealing windows and doorways at home for a study participant. Figures A and B include ambient hourly average $PM_{2.5}$ recorded at the US Embassy (navy bars), home indoors excluding cooking periods (red), cooking at home (light blue), indoors in buildings other than home and the US Embassy (orange), commuting by car (magenta), US Embassy (gray), and outdoors (green). [C] Indoor except cooking (I) $PM_{2.5}$ recorded at home compared to corresponding outdoor (O) $PM_{2.5}$ recorded by fixed site ambient monitor for pre-intervention represented in navy and post-intervention represented in orange. The slope of the I/O ratio in each session is represented by a corresponding colored long-dash line.

3.5 Regression of indoor-on-outdoor $PM_{2.5}$

The results of the (dwelling-specific) indoor-on-outdoor regression slope for all 21 participants with paired pre-post data are shown as a Forest plot in figure 4. Meta-analysis of these regression slopes indicates a summary indoor/outdoor ratio of 0.13 (95% CI 0.09, 0.17) pre-intervention and 0.07 (95% CI 0.04, 0.10) post-intervention (figure 4). The corresponding meta-analytical result of the y-intercepts of these dwelling-by-dwelling regressions was 0.09 (−0.77, 0.94) in the pre-intervention period and 0.69 (95% CI−0.78, 2.16) in the post-intervention period (figure A4). These *y*-intercepts indicate the theoretical indoor concentrations of $PM_{2.5}$ when outdoor $PM_{2.5}$ is zero.

The relationship between indoor/outdoor ratios and the capacity of the APs to clean the air in each participant’s dwelling is shown in figure 5. The regression slope of the indoor/outdoor ratios against AP capacity per m^2 floor area was −0.03 (95% CI −0.14, 0.20), indicating a weakly negative (and not statistically significant) relationship.

3.6 Sensitivity analyses

Sensitivity analyses of the dwelling-by-dwelling regression of indoor-on-outdoor $PM_{2.5}$ gave the following results: (a) restricting analysis to times when the outdoor temperature was <18°C (64.4°F) gave a summary slope (95% CI) of 0.13 (0.09, 0.17) pre-intervention and 0.04 (0.02–0.05) post-intervention; (b) restricting analysis to the 18 participants with at least eight hours of personal monitoring at home both pre- and post-intervention gave a summary slope of 0.13 (0.09, 0.17) pre-intervention and 0.07 (0.04, 0.11) post-intervention; (c) restricting analysis to monitoring sessions with high and/or middle AP settings reported gave a summary slope (95% CI) of 0.11 (0.07, 0.15) pre-intervention and 0.04 (0.02–0.06) post-intervention; (d) using data from all participants, including those with unpaired data from pre- or post-intervention periods gave a summary slope of 0.14 (0.10, 0.18) pre-intervention and 0.08 (0.06, 0.11) post-intervention (figure A5). These results therefore broadly support the findings of the main analyses based on the 21 participants with paired monitoring data.

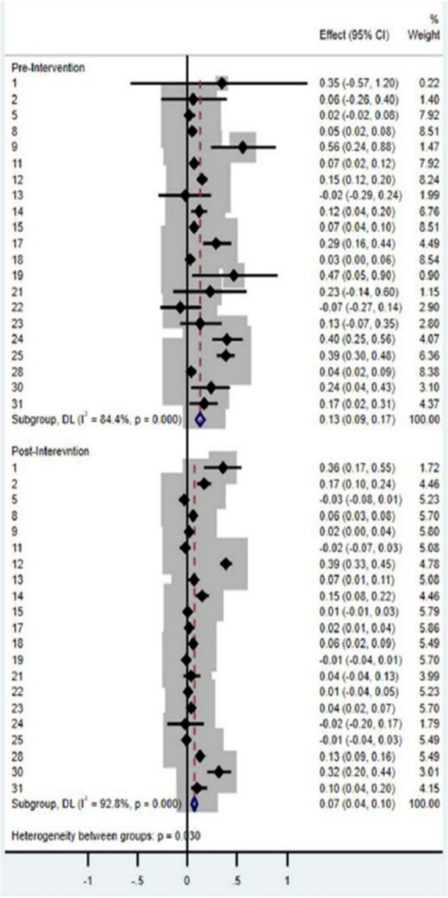


Figure 4. Meta-analysis of the dwelling-specific slopes of the indoor-on-outdoor PM2.5 ratio pre- and post-intervention, n = 21.

4. Discussion

This study provides rare evidence about the combined effect of the use of high capacity APs and improving dwelling air tightness to limit personal exposure to fine particle pollution in a setting of poorly sealed traditional dwellings and high outdoor $PM_{2.5}$ concentrations. The results suggest that such combined measures achieved a considerable reduction in the indoor/outdoor ratio of $PM_{2.5}$ concentrations—to a very low post-intervention ratio of around 0.07. This indicates a very high degree of protection in the home environment against exposure to $PM_{2.5}$ derived from polluted outdoor air.

A strength of our study was that it was based on simultaneous measurement of indoor and outdoor $PM_{2.5}$ concentrations and the dwelling-by-dwelling derivation of a regression slope for the indoor/outdoor ratio of $PM_{2.5}$. Thus, even though mean outdoor concentrations of $PM_{2.5}$ were different in the pre-intervention and post-intervention periods of monitoring, we believe the regression analyses made a reasonable correction. It would have been better still to have had measurements at similar outdoor concentrations during the pre- and post-intervention periods, but we were limited by the circumstance of the 'natural experiment', with the decision of the Embassy to provide additional home APs in the late autumn of 2019 at a time when outdoor concentrations of $PM_{2.5}$ typically increase (because of increased combustion of fuels in winter). We cannot exclude the possibility that the slightly colder weather of most of the post-intervention period may have had some impact in encouraging householders to keep windows and doors tightly closed, but our sensitivity analysis confined to times when the outdoor temperature was <18 ◦C (64.4 ◦F) gave a broadly similar result to our headline finding.

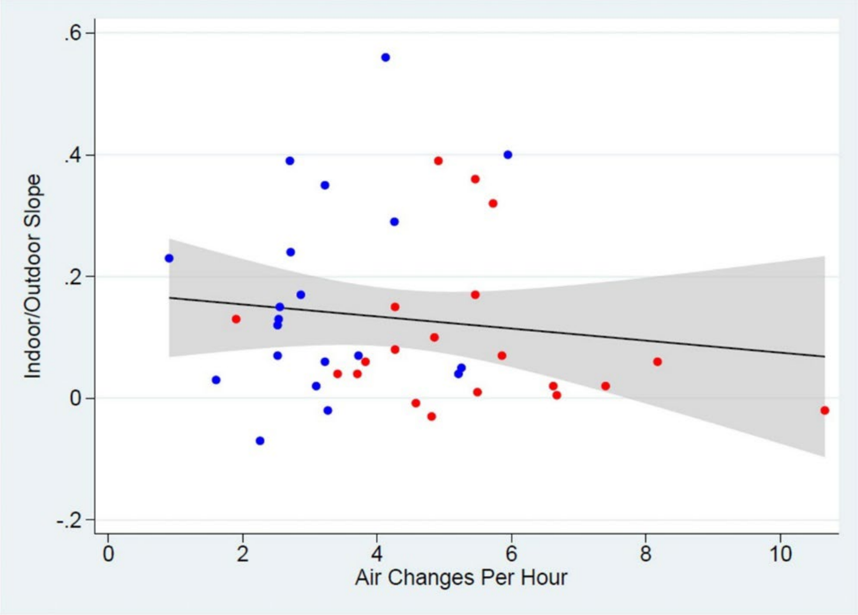


Figure 5. The slope of the regression of indoor-on-outdoor (I/O) $PM_{2.5}$ using home (indoor) $PM_{2.5}$ and corresponding fixed-site ambient (outdoor) $PM_{2.5}$ versus the air changes per hour (ACH) at home among the participants that added air purifiers excluding one participant where home size was not available, n = 20. Indoor values are when participants were at home excluding cooking periods. Blue represents measurements before adding high capacity air purifiers (pre-intervention), red represents measurements after adding air purifiers (post-intervention).

One concern was that the sealing of the home might result in higher indoor concentrations of $PM_{2.5}$ derived from indoor sources, notably cooking, despite the increase in home AP capacity. Moreover, the results used in the main analysis for the I/O ratios deliberately excluded $PM_{2.5}$ data for periods of cooking. During periods of home cooking, concentrations of indoor $PM_{2.5}$ were in fact higher post-intervention than pre-intervention. This might reflect the fact that post-intervention homes were more air-tight, and even with high capacity APs, the clearance of particle pollution generated by cooking was slower, although differences in the outdoor level again complicate interpretation. The net effect of intervention on personal exposure (non-cooking and cooking periods combined) in the home environment appears rather less impressive than the reductions in I/O ratios might suggest. But it should be noted that it is only for these ratios that our analyses fully adjust for the effect of differences in outdoor $PM_{2.5}$ concentrations during the periods of monitoring. It is pertinent that the mean concentration of $PM_{2.5}$ was higher post-intervention during cooking periods at home and commuting by car while remaining microenvironments saw higher $PM_{2.5}$ concentrations pre-intervention. Overall, personal exposure was lower in the post-intervention period despite higher outdoor concentrations. Interpreting the reasoning for the post-intervention increase in $PM_{2.5}$ while outdoors is complex. Participants decreased the amount of time they spent outdoors post-intervention which is expected given that the post-intervention monitoring occurred during the winter (December to March) when the weather was colder, and the hours of daylight were shorter than during pre-intervention monitoring (September to November). Fewer participants commuted by foot to work (with close proximity to traffic-related pollution sources) and exercised outdoors at the Phora Durbar Recreational Complex post-intervention than during the pre-intervention period.

Previous studies demonstrated that APs can appreciably reduce the concentration of indoor $PM_{2.5}$ in settings affected by wood smoke. Wheeler *et al* used one high capacity AP in dwellings with smoke generated by burning wood and found a 52% reduction in $PM_{2.5}$ measured at home compared to using a sham filter (Wheeler et al., 2014). Kajbafzadeh *et al.* conducted an intervention study using two APs (one in the living room and one in the bedroom) in dwellings with indoor woodsmoke that were in close proximity to roadway traffic and found a 40% reduction in $PM_{2.5}$ measured at home when APs were used (Kajbafzadeh et al., 2015). McNamara *et al.* examined the impact of using two Aps at home (one in the living room and one in the bedroom) among children with asthma and found that indoor $PM_{2.5}$ was reduced by 66% when APs were used (McNamara et al., 2017). In a small study in seven dwellings in an area with active wildfires, Xiang *et al.* found a 48% to 78% reduction in home $PM_{2.5}$ when using one high efficiency particulate air (HEPA) filter per dwelling (Xiang, Huang, et al., 2021). Two studies using APs in dwellings in high traffic areas provide further evidence of the use of Aps in dwellings with high ambient air pollution levels. Cox *et al.* reported the indoor/outdoor ratio decreased by 0.6 after placing one AP in the bedroom (Cox et al., 2018). A study conducted in United States' public housing dwellings in a highly trafficked area found that particle counts decreased by 21% to 68% in 15 apartments where high efficiency wall mounted APs were used (Padro-Martinez et al., 2015).

Three intervention studies in China lend further support to the capacity for APs to reduce indoor $PM_{2.5}$ in locations with high outdoor $PM_{2.5}$. In a study of indoor air quality in a variety of buildings in Beijing, Deng *et al* found that using an AP reduced the I/O ratio by 0.35–0.55 (Deng, 2017). Chen *et al.* reported a 57% decrease in indoor $PM_{2.5}$ in Shanghai university dormitory rooms when one AP was added (Chen et al., 2015). In a study of children with asthma in Shanghai, indoor $PM_{2.5}$ was reduced by 80% when one AP was used in the bedroom (Barkjohn et al., 2021). Two studies conducted in Denmark reported 46% to 63% reduction in indoor $PM_{2.5}$ levels after adding two APs in the dwelling (Brauner et al., 2008; Karottki et al., 2013). A long-term study in southern California in two communities with high ambient $PM_{2.5}$ reported a 48% decrease in indoor $PM_{2.5}$ following the use of a high efficiency AP (Bennett et al., 2022). In a controlled laboratory study, Spilak *et al.* found that APs reduced $PM_{2.5}$ by 52% with an I/O of 0.35 after 30 min of use (Spilak et al., 2016).

There are appreciably fewer studies regarding efforts to improve dwelling airtightness and impact of these efforts on indoor air quality. Yang *et al* examined adding low-cost efforts to improve the airtightness of a school in South Korea and found that sealing windows with film and adding padding to window closures helped to reduce air leakage by 37% and indoor fine dust by 22% (Yang et al., 2022). In a study of more than 200 homes in Colorado, weather stripping and sealing air handling ductwork were indicated as the two most effective measures to reduce the ingress of ambient air (Shrestha et al., 2019). Current evidence from these studies was based on a single mitigation intervention, either APs or home sealing. Here we provide evidence about the combined effect of the use of high capacity APs and increased home seal in a setting of typically poorly sealed dwellings and seasonally very high outdoor concentrations.

We identified only one other study of the combined effect of enhanced home air filtration using APs and improved air tightness to reduce indoor $PM_{2.5}$. In a study of four apartment buildings in China with varying levels of air filtration and air tightness, Wang *et al* found that the building with the highest level of filtration and air tightness had the lowest indoor $PM_{2.5}$ ($26.0 \pm 1.6\ \mu g/m^3$) and lowest mean I/O ratio (0.19 ± 0.06) (Wang et al., 2016). Wang's results, although based on just four dwellings, are consistent with the findings of our study. Our estimate of the post-intervention indoor/outdoor ratio was smaller than that of the Wang study, which may reflect the fact that the APs were high capacity (able to filter 14.2 m^3 per hour).

A key strength of our study is that it included more participants/dwellings than many previous studies. The relatively large group of participants meant that we had sufficient monitoring data to be able to implement a dwelling-by-dwelling regression analysis of the indoor-outdoor ratios of $PM_{2.5}$ in the pre- and post-intervention periods, which should have provided robust adjustment for differences in the outdoor $PM_{2.5}$ concentrations during the periods of monitoring. However, it is less easy to make similar adjustments for the spikes of indoor $PM_{2.5}$ concentrations associated with periods of cooking, so our evidence is therefore less clear on the net effect of the intervention on overall home exposure to $PM_{2.5}$ in the context of the large differences in outdoor concentrations. But, overall, the study demonstrated the impact of increasing the air purification capacity, measured by the HAPC per hour, on the $PM_{2.5}$ concentration at home and overall personal exposure even while the outdoor $PM_{2.5}$ concentration increased dramatically during the post-intervention monitoring period.

Several limitations were identified for this study. The original plan for this study was to collect one year of data with study participants wearing personal monitors four times in a calendar year or roughly once every three months. Due to COVID-19 related social distancing measures and other related policies, many study participants moved back to the United States or began teleworking from their home in Kathmandu. Study subjects had a high socio-economic status and access to high quality housing and APs and their results may not be generalizable to the population in Kathmandu but may be relevant to other diplomats, expatriates and other persons who have access to high quality housing and APs for use at home. Participants were not asked to explicitly indicate when cooking started and ended at home. Global positioning system (GPS) latitude and longitude data would have helped with the precision of microenvironment assignments, beyond what was detailed in the time activity log. GPS data collection was planned for this study but there were difficulties with data collection via cellular phone technology in Kathmandu. Home tightness was not directly measured through blower door testing or other methods to quantify improvements in home seal tightness made after the addition of tape, caulk and plastic sheeting to windows and doors. Chen *et al.* defined the infiltration factor as the 'equilibrium fraction of ambient particles that penetrates indoors and remains suspended' and the penetration factor as the 'fraction of particles in the infiltration air that passes though the building shell (Chen et al., 2015). The infiltration and penetration factor are figures that would be helpful to better understand the association between indoor and outdoor $PM_{2.5}$ levels as the indoor $PM_{2.5}$ can vary due to indoor sources of $PM_{2.5}$ including cooking, vacuuming, using a wood fireplace and other combustion-related activities in the home. This study focused on the general tendency by dwelling specific I/O slopes from multiple observations. Further improvement of measurements including the infiltration and/or penetration factors should be considered when developing future personal monitoring studies. A final limitation of the study is that indoor carbon dioxide (CO_2) was not monitored in personal residences during the study. Dwellings with a tight seal may have low level of air changes per hour and, as a result, have high CO_2 levels when people are at home and APs will not remove this excess CO_2. The CO_2 level is important to consider when improving the home tightness and CO_2 measurements in future studies could contribute to the actual air change rate per hour estimations.

The intervention described in this study included the use of high capacity APs in each dwelling. Each AP is able to clean more than twice the area of the prior APs used in Embassy dwellings. The high capacity APs are expensive, more than $500 U.S. each at the time this article was written, and the cost is likely a barrier for adoption in many homes in Nepal. APs with a high CADR are especially helpful for the homes occupied by U.S. diplomats which are typically older and with reported leaky gaps in windows and doorways that allow for the influx of outdoor $PM_{2.5}$ into the homes. Study participants were highly educated and informed about the importance of using APs in dwellings, which may mean their use of APs was better than might be assumed for a typical Nepali resident. The total of the home AP capacity per hour of all APs in participants' homes increased by 69% from 3.2 pre- to 5.4 post-intervention and findings from the study represent what could be achieved when people have access to a very high level of air purification at home. Unfortunately, most people living in highly polluted cities do not have access to as many APs as the study participants. The use of low-cost efforts such as adding caulk or weatherproofing tape to windows and unused exterior doors to improve home tightness to reduce the ingress of outdoor air pollution is something that should be considered when costs are a barrier to purchasing APs. Concern should be taken if home participants cook over an open flame or use a wood or coal stove to heat the home, efforts to improve the home tightness may not be appropriate.

Although the cost of high capacity APs may be a barrier to widespread uptake and use of this technology, options for improving home air filtration and improving home airtightness should be considered in order to reduce $PM_{2.5}$ in dwellings.

5. Conclusions

Personal monitoring in Kathmandu revealed that adding high capacity APs and improving the seal of the home to the ingress of outdoor air helped to reduce the indoor $PM_{2.5}$ level at home, even at outdoor $PM_{2.5}$ levels more than 10 times the WHO's maximum daily mean level of 15 µg/m^3. I/O ratios decreased post-intervention during the winter when outdoor $PM_{2.5}$ was high. These findings confirm that in locations with high outdoor $PM_{2.5}$, it is possible to achieve low home $PM_{2.5}$ levels and very low indoor/outdoor ratios in homes that utilize high capacity APs and enhanced air tightness.

Data availability statement

The data generated and/or analysed during the current study are not publicly available for legal/ethical reasons but are available from the corresponding author on reasonable request.

Acknowledgments

We thank Joe Beres and Claire Huson for their advice on personal exposure monitoring, Greg Martin, Wayne Quillan, Kimberly Tiffany and Todd Tiffany for their encouragement and support with project development, and Durga Godar and other staff at the U.S. Embassy in Kathmandu for assistance with data collection during this study.

Conflict of interest

The authors declare that they have no known competing financial interests or personal relationship that could have appeared to influence the work reported in this paper.

Funding information

This project was supported by the U.S. Department of State, Washington, DC and the U.S. Embassy, Kathmandu, Nepal.

ORCID iD

Leslie Edwards https://orcid.org/0000-0002-9925-4267

References

Applied Particle Technology 2020 Automated environmental health and safety (available at: https://appliedparticletechnology.com/)

Barkjohn K, Norris C, Cui X, Fang L, Zheng T, Schauer J and Bergin M H 2021 Real-time measurements of $PM_{2.5}$ and ozone to assess the effectiveness of residential indoor air filtration in Shanghai homes *Indoor Air* **31** 74–87

Bennett D H, Moran R E, Krakowiak P, Tancredi D J, Kenyon N J, Williams J and Fisk W J 2022 Reductions in particulate matter concentrations resulting from air filtration: a randomized sham-controlled crossover study *Indoor Air* **32** e12982

Blueair 2022a Classic 203 Slim (available at: www.blueair.com/us/refurbished-air-purifiers/classic-203-slim/1422.html) Blueair 2022b Classic 605 (available at: www.blueair.com/us/air-purifiers/classic-605/1641.html)

Brauner E V, Forchhammer L, Moller P, Barregard L, Gunnarsen L, Afshari A and Loft S 2008 Indoor particles affect vascular function in the aged: an air filtration-based intervention study *Am. J. Respir. Crit. Care Med.* **177** 419–25

Chen C and Zhao B 2011 Review of relationship between indoor and outdoor particles: i/O ratio, infiltration factor and penetration factor *Atmos. Environ.* **45** 275–88

Chen R *et al* 2015 Cardiopulmonary benefits of reducing indoor particles of outdoor origin: a randomized, double-blind crossover trial of air purifiers *J. Am. Coll. Cardiol.* **65** 2279–87

Cohen A J, Brauer M, Burnett R, Anderson H R, Frostad J, Estep K and Forouzanfar M H 2017 Estimates and 25-year trends of the global burden of disease attributable to ambient air pollution: an analysis of data from the global burden of diseases study 2015 *Lancet* **389** 1907–18

Cox J, Isiugo K, Ryan P, Grinshpun S A, Yermakov M, Desmond C and Reponen T 2018 Effectiveness of a portable air cleaner in removing aerosol particles in homes close to highways *Indoor Air* **28** 818–27

Cromar K R, Gladson L A, Hicks E A, Marsh B and Ewart G 2021 Excess morbidity and mortality associated with air pollution above american thoracic society recommended standards, 2017–2019 *Ann. Am. Thorac. Soc.* **19** 603–613

Deng G, Li Z, Wang Z, Gao J, Xu Z, Li J and Wang Z 2017 Indoor/outdoor relationship of $PM_{2.5}$ concentration in typical buildings with and without air cleaning in Beijing *Indoor Built Environ.* **26** 60–68

Kajbafzadeh M, Brauer M, Karlen B, Carlsten C, van Eeden S and Allen R W 2015 The impacts of traffic-related and woodsmoke particulate matter on measures of cardiovascular health: a HEPA filter intervention study *Occup. Environ. Med.* **72** 394–400

Karottki D G, Spilak M, Frederiksen M, Gunnarsen L, Brauner E V, Kolarik B and Loft S 2013 An indoor air filtration study in homes of elderly: cardiovascular and respiratory effects of exposure to particulate matter *Environ. Health* **12** 116

Klepeis N E, Nelson W C, Ott W R, Robinson J P, Tsang A M, Switzer P and Engelmann W H 2001 The national human activity pattern survey (NHAPS): a resource for assessing exposure to environmental pollutants *J. Expo. Anal. Environ. Epidemiol.* **11** 231–52

Li J, Mattewal S K, Patel S and Biswas P 2020 Evaluation of nine low-cost-sensor-based particle matter monitors *Aerosol Air Qual. Res.* **20** 254–70

McNamara M L, Thornburg J, Semmens E O, Ward T J and Noonan C W 2017 Reducing indoor air pollutants with air filtration units in wood stove homes *Sci. Total Environ.* **592** 488–94

Padro-Martinez L T, Owusu E, Reisner E, Zamore W, Simon M C, Mwamburi M and Durant J L 2015 A randomized cross-over air filtration intervention trial for reducing cardiovascular health risks in residents of public housing near a highway *Int. J. Environ. Res. Public Health* **12** 7814–38

Shrestha P M, Humphrey J L, Carlton E J, Adgate J L, Barton K E, Root E D and Miller S L 2019 Impact of outdoor air pollution on indoor air quality in low-income homes during wildfire seasons *Int. J. Environ. Res. Public Health* **16** 3535

South Coast Air Quality Monitoring District 2020 Field evaluation APT minima (available at: www.aqmd.gov/docs/default-source/aq- spec/field-evaluations/apt-minima—field-evaluation.pdf?sfvrsn=8)

Spilak M P, Sigsgaard T, Takai H and Zhang G 2016 A comparison between temperature-controlled laminar airflow device and a room air-cleaner in reducing exposure to particles while asleep *PLoS One* **11** e0166882

StataCorp 2021 Stata statistical software: release 17. (College Station, TX: StataCorp LLC) (available at: www.stata.com/support/faq/ resources/citing-software-documentation-faqs/)

United States Environmental Protection Agency 2020 AirNOW department of state (available at: www.airnow.gov/international/us- embassies-and-consulates/)

US Environmental Protection Agency 2015 Standard operating procedure for the continuous measurement of particulate matter (available at: www.epa.gov/ttnamti1/files/ambient/pm25/sop_project/905505_BAM_SOP_Draft_Final_Oct09.pdf)

Wang F, Meng D, Li X and Tan J 2016 Indoor-outdoor relationships of $PM_{2.5}$ in four residential dwellings in winter in the Yangtze River Delta, China *Environ. Pollut.* **215** 280–9

Wellenius G A, Burger M R, Coull B A, Schwartz J, Suh H, Koutrakis P and Mittleman M A 2012 Ambient air pollution and the risk of acute ischemic stroke *Arch. Intern. Med.* **172** 229–34

Wheeler A J, Gibson M D, MacNeill M, Ward T J, Wallace L A, Kuchta J and Stieb D M 2014 Impacts of air cleaners on indoor air quality in residences impacted by wood smoke *Environ. Sci. Technol.* **48** 12157–63

World Health Organization 2021 WHO global air quality guidelines: particulate matter ($PM_{2.5}$ and PM_{10}), ozone, nitrogen dioxide, sulfure dioxide and carbon monoxide (available at: https://apps.who.int/iris/handle/10665/345329)

Xiang J, Huang C H, Shirai J, Liu Y, Carmona N, Zuidema C and Seto E 2021 Field measurements of $PM_{2.5}$ infiltration factor and portable air cleaner effectiveness during wildfire episodes in US residences *Sci. Total Environ.* **773** 145642

Yang S, Yuk H, Yun B Y, Kim Y U, Wi S and Kim S 2022 Passive $PM_{2.5}$ control plan of educational buildings by using airtight improvement technologies in South Korea *J. Hazard. Mater.* **423** 126990

5.3 Postscript to research paper

My independent contributions to this paper include (1) developing study recruitment materials, (2) developing the time activity diary used by study participants, (3) recruitment of study participants, (4) creating the data collection form that diplomats used to record their daily activities, use of air purifiers and demographic characteristics, (5) the study to the London School of Hygiene and Tropical Medicine’s Research Ethics Committee for review, (6) submitting the study to the US Department of State’s

Human Subjects Protection Committee for review, (7) obtainment of personal monitoring data from a cloud-based data platform, (8) development of the database used to store personal monitoring data, (9) obtainment of the ambient data from two fixed site monitors in Kathmandu, (10) data cleaning for personal monitoring data used in the study, (11) obtainment of meteorological data including ambient temperature, rainfall and windspeed used in the analysis, (12) obtainment of the US Embassy's records of air purifiers provided to each diplomatic residence, including the date that the high capacity air purifiers were provided and installed in diplomat's residences, (13) compiling the personal monitoring data from the study participants and ambient data into a database, (14) conducting the data analysis, (15) writing the first draft of the manuscript, (16) incorporating advice from co-authors into subsequent drafts of the manuscript, (17) preparing all tables and figures included in the manuscript, (18) submitting the manuscript and related materials to the journal *Environmental Health: Research* for consideration, and (19) updating the manuscript to reflect feedback from the journal's editors. Further details about my contributions to the research are available on the Research Paper Cover Sheet (Item D) included in Section 5.2 of my thesis.

Figure 2 in the published article included ambient $PM_{2.5}$ data collected at fixed-site monitors at the US Embassy and at the Phora Durbar Recreational Complex in Kathmandu. The data in this figure was not adjusted for meteorological conditions such as temperature, wind, or precipitation.

A review of the literature identified one relevant study about the effectiveness of air purifiers that was published subsequent to my paper examining the personal exposure to $PM_{2.5}$ among US diplomats in Kathmandu. Bennett *et al*. conducted a randomized crossover study in 103 households in California to determine the effectiveness of air purifiers used in the bedroom and living room with one week indoor and outdoor time-integrated samples collected for $PM_{0.2}$, $PM_{2.5}$ and PM_{10} when true air purifiers were used and a one week period with sham air purifiers were used (Bennett et al., 2022). Study participants reported using air purifiers for at least 90% of the sampling periods. Use of the true air purifiers resulted in a 48% reduction in the indoor $PM_{0.2}$ and $PM_{2.5}$ and 31% reduction in PM_{10} in comparison to the sampling period using sham air purifiers and a 77% decrease in the indoor/outdoor (I/O) ratio.

5.4 Fulfillment of thesis objectives

The intervention study presented in this chapter fulfilled objective 2 and sub-objective 2b, as the published article detailed the quantification of the $PM_{2.5}$ exposure level for US diplomats and family members in a city with high ambient $PM_{2.5}$ by microenvironment and described the relationship between $PM_{2.5}$ personal exposure and ambient $PM_{2.5}$ after implementing enhanced mitigation measures, including high capacity air purifiers, at home. The study revealed that microenvironment responsible for a majority of diplomats' $PM_{2.5}$ exposure was their residence and that the ratio of personal to ambient $PM_{2.5}$ decreased by half, from 0.32 to 0.16, following the addition of high capacity air purifiers to diplomats' residences. The implications on health associated with the reduction in the ratio of personal to ambient $PM_{2.5}$ identified in Chapter 5 was further explored in the health model described in Chapter 6 of my thesis.

6 Mortality burden associated with $PM_{2.5}$ exposure among US diplomats: Health modelling study

6.1 Introduction

This chapter focuses on the development of a novel model to estimate the impact on mortality of living in multiple cities with varying ambient $PM_{2.5}$ concentrations for a 20-year career assignment for US diplomats and family members in three age groups including older diplomats, born in 1955 with assignments conducted between ages 45-64 years; young diplomats born in 1975 with assignments conducted between ages 25-44 years and diplomats' children, who accompanied their diplomat parent(s) on assignments from birth to age 20 years. The 20-year period of diplomatic assignments for all three age groups was from 2000-2019, in order to maximize the availability and use of ground level $PM_{2.5}$ measured data in the model. A series of ten illustrative 20-year career assignment profiles were created, and all ten assignment profiles were applied to older diplomats, young diplomats, and children. The number of years spent in Washington, DC varied in the ten assignment profiles and ranged from three years in Assignment 2 (Standard Assignment B) to 15 years in Assignment 4 (High one year & low three years cycle assignment (Table A.1 included as an appendix to the manuscript). Americans living exclusively in the US serve as the comparator group in this study. The exploratory model incorporated delays in the full impact of $PM_{2.5}$ exposure and $PM_{2.5}$-related health effects through the use of inception lags and cessation lags. The study includes estimates of the life expectancy and days of life lost (DLL) during a series of ten illustrative 20-year career diplomatic assignments where the number of years living in a city with high ambient $PM_{2.5}$ varies. Life expectancy and DLL estimates were also calculated for an assignment with enhanced mitigation available during diplomatic assignment postings in Asia and Africa that utilized the mitigation effectiveness figure calculated during the $PM_{2.5}$ personal monitoring study described in Chapter 5. Mortality was selected as the health outcome to include in the model due to the findings in the literature review (Chapter 3), with the strongest body of evidence for a change in mortality rates among persons who moved to an area with a change in ambient $PM_{2.5}$.

This manuscript addresses research objective (3) develop a health impact model to quantify the mortality burden associated with $PM_{2.5}$ exposure among a population who relocate to different cities over the world and apply the model to the US diplomats and family members with multiple international assignments including highly polluted cities, and sub-objectives (3a) quantify the health burden, in terms of mortality and life years lost, associated with $PM_{2.5}$ exposure for US diplomats and family members based on a set of 20-year career overseas assignment profiles, and (3b) quantify the degree to which the indoor $PM_{2.5}$ mitigation measures currently in use in highly polluted cities (i.e. the use of air purifiers and improving home air tightness) can mitigate such health burden. This activity is included as a research paper in chapter 6 and was submitted for publication in the journal *Environmental Health*. The supplementary material from this paper is included in Appendix 4.

6.2 Research paper

The cover sheet and research paper for this activity are included on subsequent pages, with figures and tables following the manuscript text. The manuscript was submitted to Environmental Health on 12 May 2023 and I am awaiting feedback from the journal as to whether they will accept the manuscript.

6.2.1 Research Paper Cover Sheet

London School of Hygiene & Tropical Medicine
Keppel Street, London WC1E 7HT

T: +44 (0)20 7299 4646
F: +44 (0)20 7299 4656
www.lshtm.ac.uk

RESEARCH PAPER COVER SHEET

Please note that a cover sheet must be completed <u>for each</u> research paper included within a thesis.

SECTION A – Student Details

Student ID Number	lsh1514008	**Title**	Ms.
First Name(s)	Leslie		
Surname/Family Name	Edwards		
Thesis Title	$PM_{2.5}$ Exposure and Associated Health Impacts on United States Government Diplomats and Accompanying Family Members With Multiple International Relocations: Exposure Measurement and Health Modeling Study		
Primary Supervisor	Dr. Ai Milojevic		

If the Research Paper has previously been published please complete Section B, if not please move to Section C.

SECTION B – Paper already published

Where was the work published?	N/A		
When was the work published?	N/A		
If the work was published prior to registration for your research degree, give a brief rationale for its inclusion	N/A		
Have you retained the copyright for the work?*	**No**	Was the work subject to academic peer review?	**Yes**

*If yes, please attach evidence of retention. If no, or if the work is being included in its published format, please attach evidence of permission from the copyright holder (publisher or other author) to include this work.

SECTION C – Prepared for publication, but not yet published

Where is the work intended to be published?	Environmental Health
Please list the paper’s authors in the intended authorship order:	L Edwards, J Milner, P Wilkinson, A Milojevic
Stage of publication	**Submitted**

SECTION D – Multi-authored work

For multi-authored work, give full details of your role in the research included in the paper and in the preparation of the paper. (Attach a further sheet if necessary)	My role and independent contributions to the research included planning the modeling study, data collection and analytics and developing the manuscript from the original draft to the version of the paper submitted to a journal for consideration. Specifically, I developed a protocol for the modeling study which included development of the background and rationale for the study, information about the data sources used in the model, and the model design. I researched available data sources for various aspects of the model including US mortality data stratified by age and sex, annual ambient $PM_{2.5}$ data reported by the World Health Organization, published $PM_{2.5}$ related mortality risk including the one from Global Burden of Disease, and lags in exposure and health outcomes to development inception and cessation lags. I led the data curation for the study with input from my PhD supervisors Dr. Ai Milojevic (AM), Dr. Paul Wilkinson (PW) and Dr. James Milner (JM). I developed a data platform used to generate years of life lost for males and females in the three age groups studied (children born in the year 2000, young diplomats born in 1980, and older diplomats born in 1955). I led the sensitivity analysis of this study which explored the use of various elements of the model including different concentration-response measurements, different inception and cessation lags, and US health statistics restricted to counties with similar mean income levels as the US diplomatic corps. I wrote the original draft of the manuscript and led the review and editing of the manuscript based on comments from co-authors. I led the

	submission process of this paper to a journal for consideration and am awaiting feedback from the journal. Overall, I led this paper from the initial formation of the idea to the submission to a journal for consideration, as the first author. AM, PW, and JM contributed by providing advice on the model construction and data analytics. AM and JM reviewed various drafts of this manuscript and provided comments to support the development of this manuscript, for which I am grateful.

SECTION E

Student Signature	Leslie Edwards
Date	22 January 2024

Supervisor Signature	Ai Milojevic
Date	22 January 2024

The impact of changing exposure to $PM_{2.5}$ on mortality for US diplomats with multiple international relocations: A modelling study

Leslie Edwards[a], James Milner[a], Paul Wilkinson[a], Ai Milojevic[a]

London School of Hygiene and Tropical Medicine, London, England, UK

Abstract

Background: Current evidence linking fine particulate matter ($PM_{2.5}$) exposure and mortality is primarily based on long-term exposure for persons that live in the same residence, city and/or country throughout the study, with few residential moves or relocations. We propose a novel method to quantify the health impacts of $PM_{2.5}$ for United States (US) diplomats who regularly relocate to international cities with different $PM_{2.5}$ levels.

Methods: Life table methods were applied at an individual-level to US mortality statistics using the World Health Organization's database of city-specific $PM_{2.5}$ annual mean concentrations. Global Burden of Disease concentration-response (C-R) functions were used to estimate cause-specific mortality and days of life lost (DLL) for a range of illustrative 20-year diplomatic assignments for three age groups. Time lags between exposure and exposure-related mortality risks were applied. Sensitivity analysis of baseline mortality, exposure level, C-R functions and lags was conducted. The effect of mitigation measures, including the addition of air purifiers, was examined.

Results: DLL due to $PM_{2.5}$ exposure for a standard 20-year assignment ranged from 0.3 days for diplomats' children to 84.1 days for older diplomats. DLL decreased when assignments in high $PM_{2.5}$ cities were followed by assignments in low $PM_{2.5}$ cities: 162.5 DLL when spending 20 years in high $PM_{2.5}$ cities compared to 62.6 DLL when spending one of every four years (5 years total) in a high $PM_{2.5}$ city for older male diplomats. Use of air purifiers and improved home tightness in polluted cities may halve DLL due to $PM_{2.5}$ exposure. The results were highly sensitive to lag assumptions: DLL increased by 68% without inception lags and decreased by 59% without cessation lags for older male diplomats.

Conclusion: We developed a model to quantify health impacts of changing $PM_{2.5}$ exposure for a population with frequent relocations. Our model suggests that alternating assignments in high and low $PM_{2.5}$ cities may help reduce $PM_{2.5}$-related mortality burdens. Adding exposure mitigation at home may help reduce $PM_{2.5}$ related mortality. Further research on outcome-specific lag structures is needed to improve the model.

1. Background

Strong evidence has been established that an increase in exposure to fine particulate matter air pollution equal to or smaller than 2.5 microns ($PM_{2.5}$) is associated with an increase in the risk of mortality (Cohen et al., 2017), (Pope et al., 2020). A comprehensive systematic review of cohort studies reported a 10 μg/m^3 increase in long-term $PM_{2.5}$ exposure is associated with an 8% (95% CI: 6%, 9%) increase in natural-cause mortality and all causes of mortality evaluated in the review showed statistically significant associations with $PM_{2.5}$ exposure: 11% (9%, 14%) increase for circulatory disease, 16% (10%, 21%) increase for cerebrovascular disease, 10% (3%, 18%) increase for respiratory disease and 12% (7%, 16%) increase for lung cancer per the same increment in $PM_{2.5}$ (Chen & Hoek, 2020). Another extensive systematic review including more than 25 years of cohort studies reported a similar order of excess mortality risk due to $PM_{2.5}$ exposure: 8% (95% CI: 6%, 11%) increase in all-cause mortality, and cause-specific mortality including 11% (8%, 14%) for cardiopulmonary disease and 13% (7%, 20%) for lung cancer, per 10 μg/m^3 increase in $PM_{2.5}$, respectively (Pope et al., 2020). Interestingly, the meta-analysis estimated indicated robust $PM_{2.5}$-mortality associations, but with heterogeneity among geographic regions (North America, Europe, and Asia). The most recent comprehensive systematic review evaluated the associations between long-term exposure to traffic-related air pollution (TRAP) and a wider range of adverse health outcomes including birth and respiratory outcomes for children (Health Effects Institute, 2022). The findings have provided an overall high or moderate-to-high level of confidence in the association between long-term exposure to TRAP and adverse health outcomes including all-cause mortality,

mortality due to circulatory disease, ischemic heart disease (IHD), and lung cancer as well as for asthma onset in both children and adults and acute lower respiratory infections (LRI) in children (Health Effects Institute, 2022).

In addition to epidemiological studies, a range of health impact assessment approaches have been developed for quantifying the impact of long-term $PM_{2.5}$ exposure on mortality. In 2019, air pollution was estimated to contribute to 6.7 million deaths globally, including 4.1 million deaths attributable to ambient $PM_{2.5}$ and 2.2 million deaths attributable to household air pollution (Fuller et al., 2022), (Health Effects Institute, 2023). The Global Burden of Disease (GBD) 2019 study estimated that ambient particulate matter was the seventh highest risk factor globally in terms of disability adjusted life years (DALYs) and household air pollution was the tenth highest (GBD Risk Factors Collaborators, 2020b) While the association between $PM_{2.5}$ and mortality has been well documented in the literature, little information is available about the impact of exposures that vary over time, such as those due to multiple international relocations. A recent systematic review of the health effects of $PM_{2.5}$ on persons with frequent relocations identified 12 studies that reported a difference in health effects among persons who relocated and non-relocated persons (Edwards et al., 2022). These included a study among United States' Medicare recipients that reported an increase in the hazard ratio (HR) for all-cause mortality per 10 $\mu g/m^3$ increase in $PM_{2.5}$ among persons who relocated, with greater effects noted among white persons (HR=1.21; 95% CI: 1.20, 1.22) than African American persons (1.12; 1.08, 1.15) (Awad et al., 2019). A reanalysis of the US Harvard Six Cities Study reported RRs for all-cause mortality per 18.6 $\mu g/m^3$ increment of $PM_{2.5}$ stratified by movers (1.08; 95% CI: 0.67, 1.76) and non-movers (1.30; 1.10, 1.54), although there was limited statistical power for the findings among movers (Krewski et al., 2003). Finally, a study of congestive heart disease (CHD) deaths according to proximity to highly trafficked roads among persons in western Canada reported a lower RR of CHD death among persons who moved further away from traffic (RR=1.14; 95% CI: 0.95, 1.37) than persons who moved closer to traffic (1.20; 1.00, 1.43) (Gan et al., 2010). While these studies provide evidence of the impacts on mortality among persons with relocations, they do not address the impact of multiple relocations to areas with large changes in ambient $PM_{2.5}$ concentrations.

When frequent changes of exposure are involved, the lag between the time when exposure changes and the time when the resulting health effect is evident becomes crucial. The time lag between reduced exposure and its impact on mortality (the 'cessation lag') has been explored by the US Environmental Protection Agency (EPA) who proposed a biphasic lag (United States Environmental Protection Agency, 2004) in which the mortality risk evolves in two distinct phases to reach a minimum level after 20 years. This lag was informed by prior studies including a study of air pollution reductions resulting from a ban on the sale of coal in Dublin, a model developed by Leksell and Rabi of the reduction in $PM_{2.5}$ and its impact on life expectancy based on several large cohort studies in the US and Europe, and other research on disease incidence including bronchitis, diminished lung functioning and lung cancer (Clancy et al., 2002; Leksell & Rabl, 2001). The proposed 'inception lag' (i.e., the lag representing increased health risk following an increase in exposure) followed the inverse pattern of the cessation lag. Other lag functions varying in shape and duration, specifically with different non-linear slopes and timing, have been proposed for all-cause and individual cause-specific mortality (Walton, 2010). They include a steep eight-year lag based on findings from the Harvard Six Cities study for $PM_{2.5}$ exposure and all-cause mortality (Laden et al., 2006) and a 38-year triphasic lag based on smoking cessation studies and lung cancer (Ben-Shlomo et al., 1994), (Knoke et al., 2008), (Walton, 2010).

The US diplomatic corps is a dynamic population with international relocations every one to six years, the timing of which depends on the diplomat's area(s) of expertise, their US government agency and related agency staffing policies. The location of each relocation is determined by the diplomat's agency and global staffing needs. Diplomats often have limited input into location decisions, particularly for career foreign service officers, however, preference may be given to diplomats with increasing seniority. Specific city assignments, or postings, are contingent upon medical clearance both for the employee and for their accompanying family members (United States Department of State, 2022a). Time lags between exposure and exposure-related health effects are of particular concern among this population as the duration of assignment in each city is generally relatively short (often 2-3 years) and air pollution levels could vary dramatically from one assignment city to the next.

The health impacts of air pollution during international assignments for diplomats and their family members are of great concern to the US government and are one of many occupational health risks diplomats face. The US government has explored mitigation options to help reduced air pollution exposure for diplomats and their family members while working in cities with high $PM_{2.5}$ including the filtration of air with air purifiers (APs) in offices and residences and improving home airtightness through taping or caulking windows and doorways. A study of 21 US diplomats in Kathmandu, Nepal found that the ratio of personal/ambient (P/A) $PM_{2.5}$ was 0.32 when a moderate to high level of mitigation was already used at home. After additional high capacity APs were added in residences, the P/A ratio was halved to 0.16 (Edwards et al., 2023). There are a few other reports on the impact of using APs on indoor air quality in the US, Beijing, and Shanghai (Padro-Martinez et al., 2015) (Deng, 2017) (Barkjohn et al., 2021). However, the results seem to vary among settings.

To fill the research gap on the health impact of air pollution exposures that vary over time, this study aims to develop a model to estimate the impact of frequent international relocations on mortality due to $PM_{2.5}$ and to apply the model to US diplomats in a variety of contrasting assignment scenarios. The model explores the effects of different assumptions regarding lags between exposure and health impacts and also examines the impact of exposure mitigation measures on the mortality estimates.

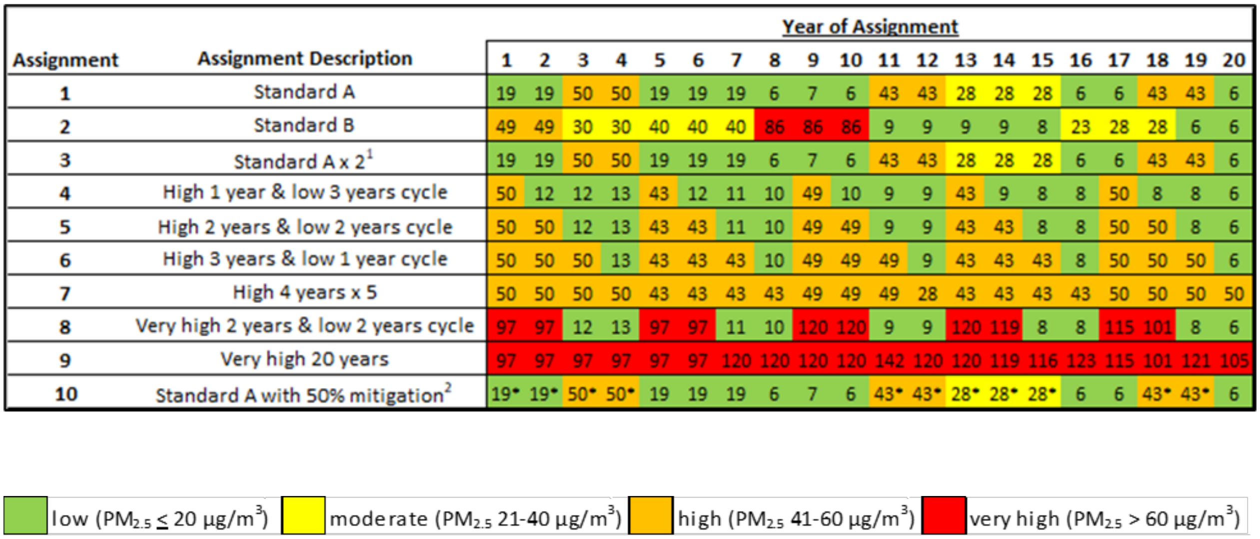
2. Methods

The model described in this exploratory analysis was applied to illustrative persons in three age groups (representing US diplomats and their families) in a variety of hypothetical 20-year assignment scenarios from 2000-2019 and was based on US mortality rates adjusted to account for time spent in locations with different levels of $PM_{2.5}$.

2.1 Diplomatic assignments

Ten hypothetical assignments were created for this analysis. The assignments and mean annual $PM_{2.5}$ concentrations in each assignment location are shown in Figure 1 and a list of all assignment locations is included in Table A.1. The assignments were developed to demonstrate a range of patterns of air pollution exposure and were based on typical international postings for US diplomats with occasional rotations in Washington, DC. The first two assignments, Standard A and Standard B, were based on the actual assignment histories for two former diplomats. Further variations of the Standard A assignment were used as follows: a longer assignment of 40 years from ages 25 to 64 years (Assignment 3); a cycle with one year in a city with high ambient $PM_{2.5}$, followed by a greater number of years in a less polluted city (Assignment 4), and vice versa (Assignment 6); the same number of years of postings in highly polluted and less polluted cities (Assignments 5 and 8); highly polluted cities only (Assignment 7 and 9); and with enhanced air pollution mitigation measures including air purifiers used in personal residences and in the workplace in highly polluted cities (Assignment 10). All assignments are for 20 years, except for Assignment 3. The ten assignments will be applied to persons in three age groups, including older diplomats, young diplomats and children who accompanied their diplomat parent(s) on assignments (see section 2.3 for further details).

Figure 1: Annual mean $PM_{2.5}$ concentration in each city for the ten assignment profiles. Each of the assignment profiles had a 20 year duration except for profile 3 which had a 40 year duration.



Assignment	Assignment Description	Year of Assignment																			
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
1	Standard A	19	19	50	50	19	19	19	6	7	6	43	43	28	28	28	6	6	43	43	6
2	Standard B	49	49	30	30	40	40	40	86	86	86	9	9	9	9	8	23	28	28	6	6
3	Standard A x 2[1]	19	19	50	50	19	19	19	6	7	6	43	43	28	28	28	6	6	43	43	6
4	High 1 year & low 3 years cycle	50	12	12	13	43	12	11	10	49	10	9	9	43	9	8	8	50	8	8	6
5	High 2 years & low 2 years cycle	50	50	12	13	43	43	11	10	49	49	9	9	43	43	8	8	50	50	8	6
6	High 3 years & low 1 year cycle	50	50	50	13	43	43	43	10	49	49	49	9	43	43	43	8	50	50	50	6
7	High 4 years x 5	50	50	50	50	43	43	43	43	49	49	49	28	43	43	43	43	50	50	50	50
8	Very high 2 years & low 2 years cycle	97	97	12	13	97	97	11	10	120	120	9	9	120	119	8	8	115	101	8	6
9	Very high 20 years	97	97	97	97	97	97	120	120	120	120	142	120	120	119	116	123	115	101	121	105
10	Standard A with 50% mitigation[2]	19*	19*	50*	50*	19	19	19	6	7	6	43*	43*	28*	28*	28*	6	6	43*	43*	6

🟩	low ($PM_{2.5} \leq 20$ µg/m^3)	🟨	moderate ($PM_{2.5}$ 21-40 µg/m^3)	🟧	high ($PM_{2.5}$ 41-60 µg/m^3)	🟥	very high ($PM_{2.5} > 60$ µg/m^3)

[1] The "Standard A x 2" assignment includes the Series A assignment repeated for a total duration of 40 years

[2] In this assignment, diplomats used air purifiers in their residences while working in cities in Africa and Asia during years indicated with an asterisk (*).

2.2 Estimation of city specific $PM_{2.5}$ exposure

All assignments were modelled for the years 2000 to 2019, except for assignment 3 ("Standard A x 2") which covered 2000 to 2039. Each city was assigned an annual average $PM_{2.5}$ concentration based on published estimates. In most cases, the estimated ambient $PM_{2.5}$ concentration published in the World Health Organization's (WHO) ambient air pollution database was used (World Health Organization, 2022). In instances where the $PM_{2.5}$ level was not available in the WHO database for the relevant year, the annual mean $PM_{2.5}$ for the nearest year was used. For time spent in the United States, US national and Washington, D.C. observed annual mean $PM_{2.5}$ levels reported by the US Environmental Protection Agency were used for years 1999 to 2021 (United States Environmental Protection Agency, 2018). To represent previous exposure, US annual mean $PM_{2.5}$ figures for the years 1981 to 2000 were taken from estimates by Meng *et al*. (Meng et al., 2019) using a chemical transport model (GEOS-Chem) with geographically weighted regression (GWR) adjustment of satellite remote sensing and ground based $PM_{2.5}$, PM_{10} and total suspended particle (TSP) measurements, when available (Meng et al., 2019). For years 1955 to 1980, 22.1 $\mu g/m^3$ was used as the annual $PM_{2.5}$ for the US as this was the estimated annual mean for 1981 reported by Meng *et al*. For years 2001 to 2021, US annual mean $PM_{2.5}$ figures reported by the US Environmental Protection Agency were used in the model and for years 2022 to 2045, 8.0 $\mu g/m^3$ was used as the annual $PM_{2.5}$ for the US as this was the annual mean for 2021.

2.3 Quantification of the impact on mortality

Mortality rates based on routine US statistics (see 2.3.3) were used to represent those of diplomats in three age groups: (1) an older diplomat born in 1955 with assignments conducted between ages 45-64 years, (2) a young diplomat born in 1975 with assignments conducted between ages 25-44 years and (3) a child, who accompanied their diplomat parent(s) on assignments from birth to age 20 years**.** A standard life table method was used to estimate life expectancy and days of life lost (DLL) for each age group following each of the 10 assignments using the method described below (Miller & Hurley, 2003). The results were compared to those assuming the individual lived exclusively in the US over the same period.

2.3.1 GBD concentration-response functions

For each year of each assignment, we applied the GBD's meta-regression, Bayesian, regularised, trimmed (MR-BRT) (GBD Risk Factors Collaborators, 2020b) concentration-response (C-R) functions to calculate the risk of $PM_{2.5}$-related mortality in relation to the theoretical minimum-risk exposure level (TMREL) estimated by the GBD study for six outcomes: IHD, stroke, chronic obstructive pulmonary disease (COPD), LRI, type 2 diabetes mellitus, and lung cancer. The GBD C-R functions are based on the ambient $PM_{2.5}$ concentration and, for IHD and stroke, vary by (5-year) age groups beginning at age 25 years. The IHD and stroke functions do not include any added risk for persons under age 25. Figure A.1 shows the GBD C-R functions for each outcome.

2.3.2 Inception and Cessation Lags

As our central estimate of the lag between change in exposure and change in risk, the mortality risks calculated for each location using the GBD functions were lagged using the 20-year cessation lag published by the US Environmental Protection Agency (EPA) (Leavitt, 2004) and a 20-year inception lag assumed to be the inverse of the EPA cessation lag (Figure A.2). The EPA 20-year cessation lag retains 70% of the risk associated with the difference in the previous year's elevated $PM_{2.5}$ concentration to account for short-term effects. During the next four years, the risk decreases by 12.5% per year, reaching a level of 20% risk distributed evenly over the course of the remaining 15 years with risk reduced by 1.3% per year to account for long-term effects of $PM_{2.5}$ exposure on lung cancer mortality (Kenfield et al., 2008; Knoke et al., 2008). During the first year of the (inverse) EPA inception lag, 30% of the risk is applied in the first year. During years two to five, the risk increases by 12.5% per year and during years six to twenty, the risk increases by 1.3% per year. After 20 years, the full risk is applied to the mortality rates.

To apply the lags in this analysis, we first calculated the RR of the risk in the prior location relative to the risk in the next location (i.e., the risk for the old location divided by the risk of the new location). When moving to a new location with an increase in $PM_{2.5}$, the inception lag was applied only to the RR for the new location (location B) divided by the RR of the prior location (location A) minus 1:

$$lagged\ risk, moved\ from\ location\ A\ (low\ PM_{2.5})\ to\ B\ (high\ PM_{2.5}) = \frac{RR_B}{RR_A} - 1$$

When moving to a new location with a decrease in $PM_{2.5}$, the cessation lag was applied to the RR for the prior location (location A) divided by the RR of the new location (location B) minus 1:

$$lagged\ risk, moved\ from\ location\ A\ (high\ PM_{2.5})\ to\ B\ (low\ PM_{2.5}) = \frac{RR_A}{RR_B} - 1$$

Risks were lagged when the ambient $PM_{2.5}$ mean changed by +/- 5 μg/m^3. Table A.2 presents example calculations using an inception lag and a cessation lag. The remaining portion of the inception lag was removed from the risk calculation when a diplomat moved to a location with lower ambient $PM_{2.5}$ while the (previous) inception lag was still evolving. Similarly, the remaining portion of the cessation lag was removed from the calculation when a diplomat moved to a location with higher ambient $PM_{2.5}$.

2.3.3 Impacted mortality rate calculations including added risk due to PM$_{2.5}$

US 2019 mortality rates (MRs) by age and gender were obtained for all-causes and each of the six pollution-sensitive conditions using International Classification of Diseases, 10th revision (ICD-10) codes specified in the GBD 2019 risk estimate publication (Centers for Disease Control and Prevention, 2021) (GBD Risk Factors Collaborators, 2020b). For each pollution sensitive condition, impacted mortality rates (iMRs) were calculated by multiplying the GBD-derived RRs by the US MRs.

The remaining, non-pollution sensitive (NPS) MR at each age was calculated by subtracting the US MR for each of the six pollution sensitive conditions from the US all-cause MR at that age. The iMRs for the six pollution sensitive conditions were added back to the NPS MR at each age to yield a new all-cause iMR.

2.3.5 Life expectancy, days of life lost and excess deaths

The probability at age ***a*** of surviving to the next year of age was calculated using the standard life table method, assuming that deaths occur at the mid-point of the year:

$$survival\ probability_a = \frac{2 - all\ cause\ iMR_a}{2 + all\ cause\ iMR_a}$$

Remaining life expectancy at birth, noted as *b*, was calculated by adding the life years from birth to 100 years' age (noted as *j* in the formula) divided by the cumulative survival during year *j*:

$$life\ expectancy_b = \frac{\sum life\ years_j}{cumulative\ survival_j}$$

Days of life lost (DLL) were calculated by subtracting the life expectancy under each assignment from the life expectancy calculated for the same diplomat living exclusively in the US. Deaths, expressed per one million population, were calculated by multiplying the impacted all-cause mortality rate for each year of age by one million and summing the number of deaths during *j*. Deaths were calculated for male and female diplomats in each of the three age groups as well as for persons of comparable age and sex diplomats that lived exclusively in the United States. Similarly, excess deaths, expressed per million population, were calculated as the additional deaths among diplomats compared to a person of the same age and sex who lived exclusively in the United States. All key assumptions for the modelling are presented in Table A.3.

2.4 Impact of mitigation at home and in workplace

In assignment 10, we explored the potential effects of using exposure mitigation strategies, including air purifiers and home sealing, to reduce the $PM_{2.5}$ concentration in the homes and workplaces of diplomats working in cities in Africa and Asia. The air in most US Embassy and Consulate buildings is highly filtered and the US government provides air purifiers to US diplomats working in many cities in Africa and Asia (United States Department of State, 2018). According to the results from our previous personal monitoring study among US diplomats in Kathmandu, Nepal, the ratio of mean *personal* $PM_{2.5}$ exposure to mean *ambient* $PM_{2.5}$ was reduced by 50% (from 0.32 to 0.16) following the addition of enhanced mitigation in diplomats' residences (Edwards et al., 2023). These findings were applied to the "Standard A with mitigation assignment" by using 50% of the city-year specific $PM_{2.5}$ exposure level during international assignments in Africa and Asia.

2.5 Sensitivity Analysis

We conducted eight sensitivity analyses to examine the sensitivity of the model results to key assumptions/parameters using the Standard A assignment. Variation 1 used US mortality statistics from the top 5% of US counties according to total household income (United States Census Bureau, 2021)) to reflect the fact that the baseline mortality for diplomats is likely to be lower than the US average population. To test the sensitivity of the model to the chosen lag structures, Variations 2 to 6 used alternate lag structures applied to the GBD C-R functions: Variation 2 used a steep eight-year lag applied to COPD and LRI only (no change in other four causes); Variation 3 used a longer 38-year triphasic lag for lung cancer only (no change in other five causes); Variation 4 applied only the cessation lag (i.e. no inception lag, assuming the full effect from the first year in a new location with higher $PM_{2.5}$ level); Variation 5 applied only the inception lag (i.e. no cessation lag, assuming the increased mortality risk associated with time spent in a location with high $PM_{2.5}$ was discontinued upon leaving that location); and Variation 6 applied no lagged effects. Figure A.2 includes plots of the lags used in variations 2 (short lag applied to COPD and LRI) and 3 (long lag applied to lung center). To assess the effects of uncertainty in the C-R functions, Variations 7 and 8 used the upper and lower limits of the 95% confidence intervals around the GBD functions.

<u>3.0 Results</u>

3.1 Mortality Rates for Pollution Sensitive Conditions

Figure 2 shows cause-specific lagged relative risks (RR) of mortality across the life course (from birth to 100 years) for an older diplomat in the Standard A assignment.

There were no lags applied prior to the beginning of the diplomatic assignment and an inception lag was applied during years 1-4, 11-14, and 18-19 of the Standard A assignment when the diplomat lived in a city with ambient annual $PM_{2.5}$ that was at least 5 μg/m^3 greater than the prior city location and a cessation lag was applied during years 5-10, 15-17, and 20 when the diplomat moved to a city with ambient annual $PM_{2.5}$ at least 5 μg/m^3 less than the prior city's $PM_{2.5}$ annual mean. A cessation lag was also applied at the conclusion of the diplomatic assignment from age 65-84 years.

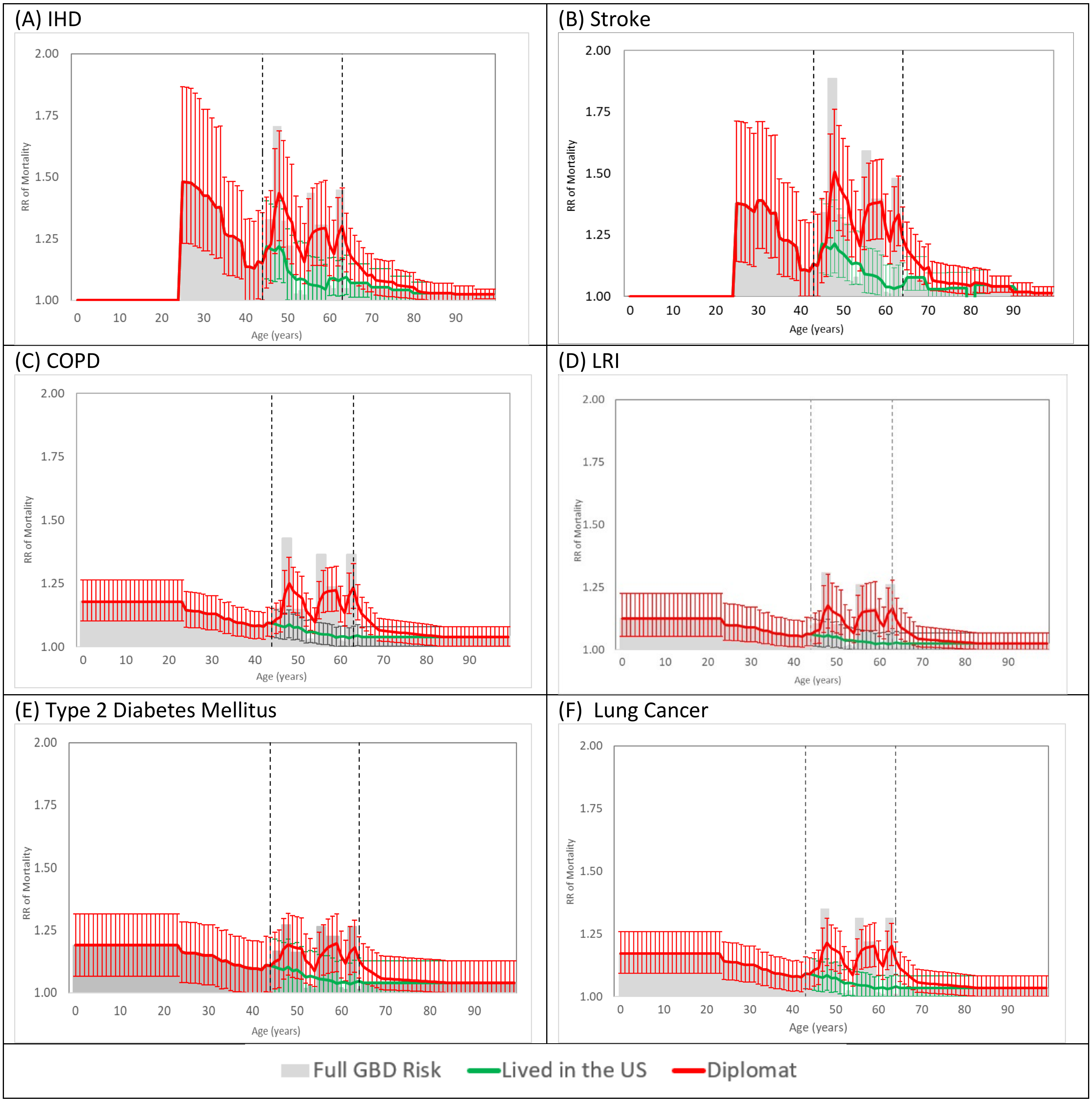


Figure 2: Lagged risk relative (RR) of mortality for (A) IHD (B) stroke (C) COPD (D) LRI (E) type 2 diabetes mellitus and (F) lung cancer for an older diplomat in the Standard A assignment (red) and for a person living exclusively in the US (green). The full GBD risk (not lagged) is shown by grey bars. Vertical dashed lines show the beginning and end of the 20 year diplomatic assignment period. Mid-points connected with a thick line represent the average RR with error bars for the lower to the upper 95% confidence intervals.

After the older diplomat began the Standard A assignment at age 45, among the six pollution-sensitive conditions, the greatest difference between RRs for the diplomat compared to the RR for the person who lived exclusively in the US was observed for stroke (Figure 2B) during the fifteenth year of the assignment, during the third and final year working in Bangkok, Thailand with an RR of 1.39 (95% CI: 1.23, 1.57) and mean annual $PM_{2.5}$ of 27 μg/m^3. During the same year, the RR of stroke for a person living in the US was 1.07 (1.0, 1.17) and mean annual $PM_{2.5}$ of 9 μg/m^3. During the course of the 20-year Standard A assignment, the RRs of mortality for each of the six pollution sensitive conditions have three distinct peaks, each occurring at the conclusion of a series of years with consecutively increasing ambient $PM_{2.5}$ levels. The pollution sensitive condition with the second greatest annual difference in RR of mortality during the Standard A assignment for a diplomat compared to a person living in the US was for IHD, with an RR of 1.29 (95% CI: 1.14, 1.49) and mean annual $PM_{2.5}$ of 27 μg/m^3 (Figure 2A). During the same year, the RR of IHD for a person living in the US was 1.04 (95% CI: 1.00, 1.15) and mean annual $PM_{2.5}$ of 9 μg/m^3, and the confidence intervals (CIs) for the diplomat and the person of comparable age living in the US overlap. The RRs of mortality for IHD and stroke are elevated before the diplomat began the Standard A assignment at age 45 and these RRs are reflective of the GBD C-R functions based on US $PM_{2.5}$ levels. Figure A.3 shows the pollution sensitive condition iMRs for an older diplomat in the Standard A assignment.

Figure 3 shows the deaths per million due to all-causes that incorporates the individual pollution sensitive iMRs for female older diplomats in various assignments. The assignment “High 3 years & low 1 year cycle” has the highest impacted mortality rate each year compared to the other assignments for most of the 20-year assignment period, from ages 45-64, although the CIs for the three assignments overlap in 19 of the 20 years of diplomatic postings. The CIs for the “High 3 years & low 1 year cycle” and the “High 2 years & low 2 years cycle” assignments do not overlap with the CIs for the US iMRs. However, the CIs for the assignment with the least number of years in a location with high $PM_{2.5}$, “High 1 year & low 3 years cycle”, overlap with the CIs for the US iMRs during 19 of the 20 years of the diplomatic assignments. Beginning at age 65 after the completion of the assignments, the iMRs for the three assignments gradually decline to the US MR.

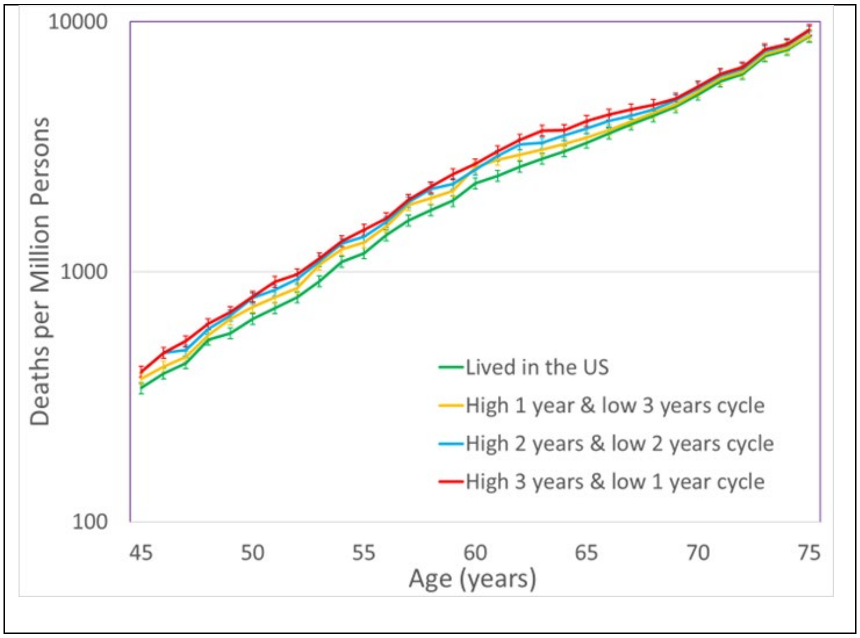


Figure 3: Age-specific deaths per million for female older diplomats in three assignments with variation in the number of consecutive years in cities with high $PM_{2.5}$ concentration and for females of comparable age living in the US.

3.3 Excess deaths due to international assignments

During the Standard A and Standard B assignments, older diplomats had a greater number of excess deaths due to international assignments, than young diplomats and children accompanying a parent on diplomatic assignments (Table 1). During the Standard A assignment, older diplomats (12,246.8 deaths per one million males, 6,640.7 deaths per one million females) had 8 times as many excess deaths as young diplomats (1,527.9 deaths per one million males, 708.6 deaths per one million females) and more than a 600-fold increase in excess deaths compared to a child accompanying their parent(s) on a diplomatic assignment (20.1 deaths per one million males, 12.1 deaths per one million females). Among the assignments examined, older diplomats living in one city with very high $PM_{2.5}$ for 20 years had the highest number of excess deaths due to international assignments (49,140.4 deaths per one million males, 28,758.3 deaths per one million females), followed by living in a series of high $PM_{2.5}$ cities in the assignment “High 4 years x 5” (29,658.2 deaths per one million males, 16,517.3 deaths per one million females). Excluding assignments with multiple years spent in cities with very high $PM_{2.5}$ ($PM_{2.5} > 60$ μg/m^3), for older diplomats in assignments with one, two or three of every four years living in locations with high $PM_{2.5}$ ($PM_{2.5}$ annual mean between 41 to 60 μg/m^3), the highest number of excess deaths were found during assignments with the highest number of years in cities with high $PM_{2.5}$ locations, including the assignments “High 3 years & low 1 year cycle” (22,120.1 deaths per one million males, 12,329.7 deaths per one million females), “High 2 years & low 2 years cycle” (15,496.9 deaths per one million males, 8,555.1 deaths per one million females) and “High 1 year & 3 low years cycle” (10,009.2 deaths per one million males, 5,409.8 deaths per one million females).

Table 1: Number of excess deaths[1] per one million persons for each diplomatic assignment[2] compared to deaths per one million Americans living exclusively in the US, by different age groups

		Older diplomat			Young diplomat			Child	
Assign-ment	Assignment description[3]	Excess deaths, male	Excess deaths, female		Excess deaths, male	Excess deaths, female		Excess deaths, male	Excess deaths, female
1	Standard A	12,246.8	6,640.7		1,527.9	708.6		20.1	12.1
2	Standard B	10,568.4	5,623.3		1,341.8	562.7		43.7	27.9
3	Standard A x 2	n/a	n/a		14,370.6	7,896.7		n/a	n/a
4	High 1 year & low 3 years cycle	10,009.2	5,409.8		1,171.2	536.3		40.7	26.7
5	High 2 years & low 2 years cycle	15,496.9	8,555.1		2,050.4	975.8		60.3	37.9
6	High 3 years & low 1 year cycle	22,120.1	12,329.7		3,007.8	1,466.6		75.7	44.4
7	High 4 years x 5	29,658.2	16,517.3		7,695.6	5,211.2		86.8	53.1
8	Very high 2 years & low 2 years cycle	24,988.7	14,514.8		3,304.8	1,678.9		108.5	70.7
9	Very high 20 years	49,140.4	28,758.3		6,332.1	3,321.5		163.5	103.8
10	Standard A with mitigation[4]	4,119.6	2,117.3		406.0	148.8		-1.8	-0.9

[1] The number of excess deaths per year *i* is calculated by subtracting the number of deaths during year i per 1 million persons of the same age and sex living exclusively in the US from the number of deaths during year i per 1 million diplomats completing a diplomatic assignment. The number of excess deaths listed on this table is the sum of excess deaths for each year from birth to age 100.

[2] See Appendix Table 1 for a list of cities and number of years in each city during the 10 assignments and see Figure 1 for the annual mean $PM_{2.5}$ levels used in the calculations.

[3] Ambient $PM_{2.5}$ level descriptions include low ($PM_{2.5}$<20 µg/m^3), moderate ($PM_{2.5}$ 21-40 µg/m^3), high ($PM_{2.5}$ 41-60 µg/m^3) and very high ($PM_{2.5}$>61 µg/m^3).

[4] In this assignment, diplomats used air purifiers in their residences while working in cities in Africa and Asia.

3.3 Life expectancy and days of life lost (DLL)

Older diplomats had greater DLL than young diplomats in the Standard A assignment (80.4 DLL vs. 10.4 DLL) and in the Standard B assignment (84.1 DLL vs. 25.0 DLL) (Figure 4). Similar trends were found for females, although the magnitude of impact was smaller than that of males. Among older male diplomats, the greatest DLL were observed during the assignment in one city with very high $PM_{2.5}$ for 20 years, “Very high 20 years” (287.8 DLL), followed by serving in four cities with high $PM_{2.5}$ for a total of 20 years, “High 4 years x 5” (176.9 DLL), and an equal number of years in cities with very high $PM_{2.5}$ and low $PM_{2.5}$, “Very high 2 years & low 2 years” (152.8 DLL). Among older male diplomats completing assignments with one, two or three of every four years in a city with high $PM_{2.5}$, the “High 3 years & 1 low year cycle” (132.9 DLL) assignment had the highest number of DLL among older male diplomats. The magnitude of DLL decreased as the number of years in cities with high $PM_{2.5}$ per four year cycle decreased to a low of 72.4 DLL while serving in the assignment with one year in a city with high $PM_{2.5}$,“High 1 year & low 3 years cycle”. A male completing a 40-year assignment, “Standard A x 2” from ages 25-64 years (89.7 DLL) had only slightly higher DLL than a male completing the Standard A assignment for 20 years from ages 45-64 (80.4 DLL).

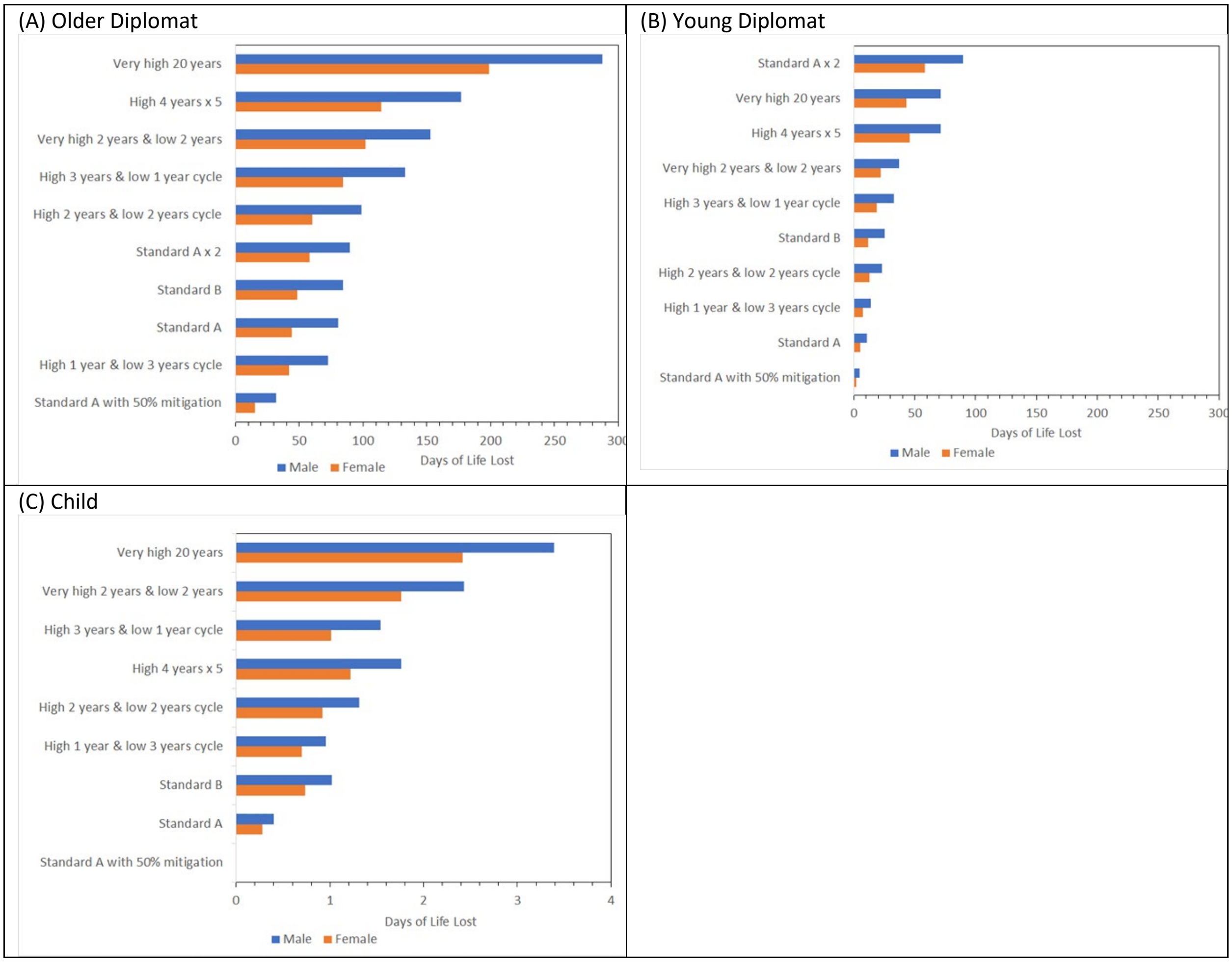


Figure 4: Days of life lost (DLL) associated with international diplomatic assignments for (A) an older diplomat, (B) a young diplomat and (C) a child accompanying their parent(s) on diplomatic assignments.

3.5 Impact of Using Room Air Cleaners and Other Exposure Mitigation

Including air pollution mitigation measures, RRs of cause-specific mortality for an older diplomat in the Standard A assignment (Figure 5) were much closer to that of an American of comparable age and sex living exclusively in the US than in the Standard A assignment without mitigation. Examining the number of excess deaths among male diplomats for the Standard A assignment with mitigation compared to the Standard A assignment without mitigation, excess deaths decreased by 66% for older diplomats (from 12,246.8 to 4,119.7 deaths per million), 73% for young diplomats (from 1,527.9 to 406.0 deaths per million) and 49% for children of diplomats (from 3.5 to 1.8 deaths per million) (Figure 6). Among males the DLL decreased by 60% for older diplomats (from 80.4 to 32.0 DLL), 55% for young diplomats (from 10.4 to 4.7 DLL) and results were similar in both scenarios for children (0.4 and -0.1 DLL) (Figure 4).

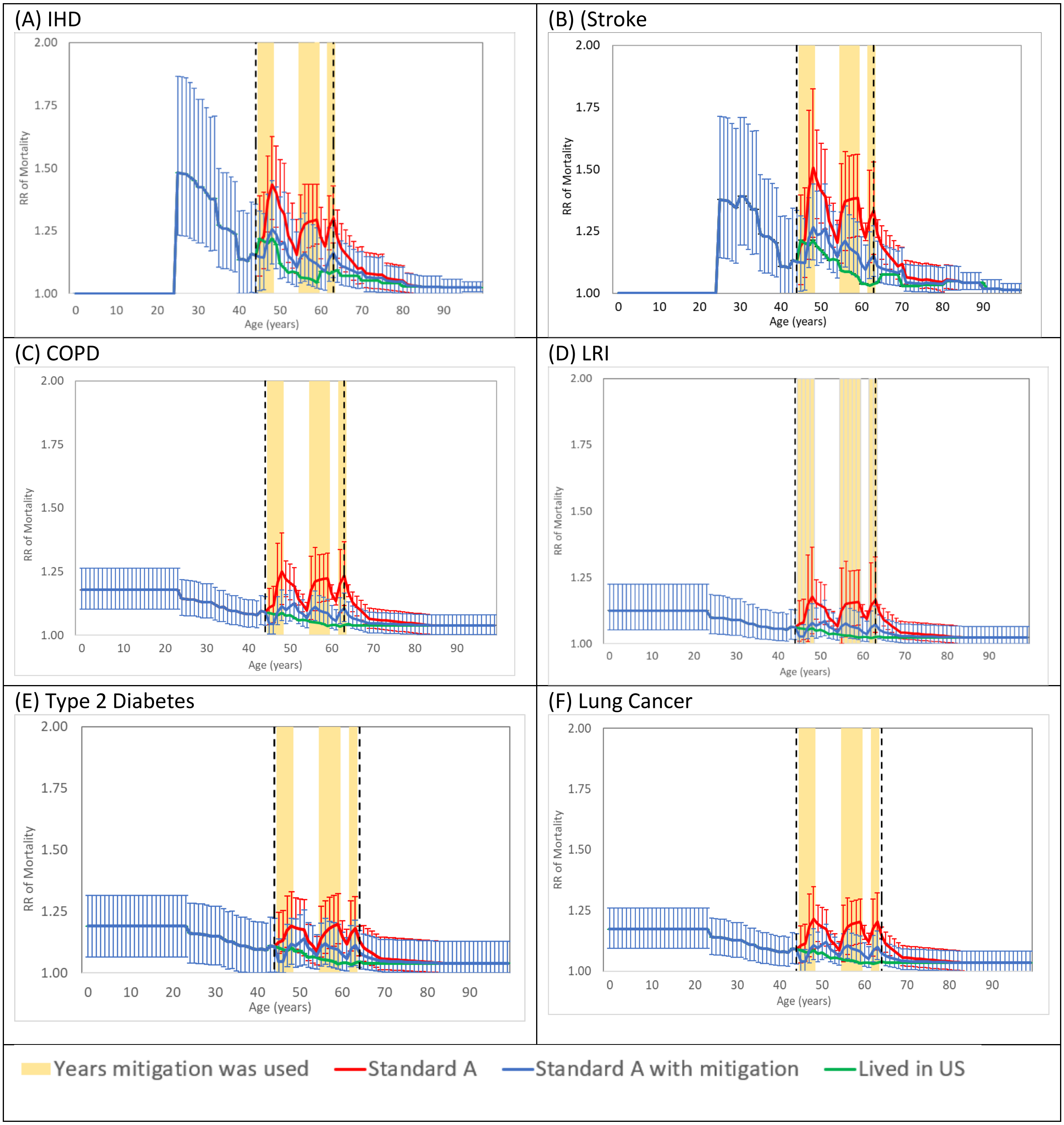


Figure 5: Relative Risks (RRs) of mortality due to ambient PM2.5 for the Standard A assignment and the Standard A assignment with mitigation with RRs for (A) IHD (B) Stroke (C) COPD (D) LRI (E) type 2 diabetes and (F) lung cancer. The RRs for a person of comparable age living in the US are indicated in green. The years with mitigation used at home are highlighted in yellow. The beginning and end of the 20 year period with diplomatic assignments are indicated by vertical dashed lines.

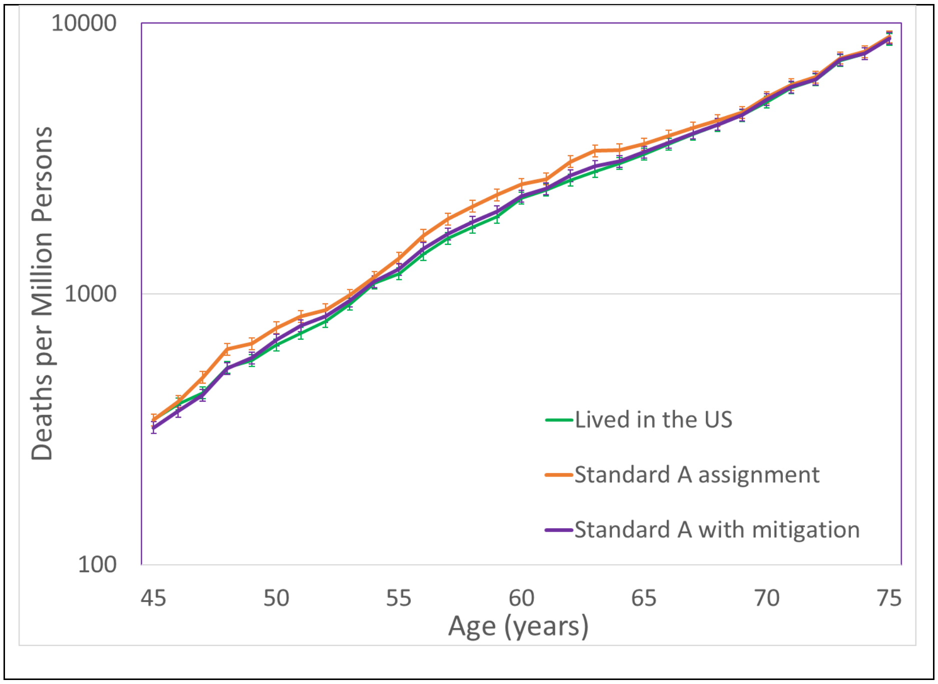


Figure 6: Deaths per one million female older diplomats in the Standard A assignment without mitigation in diplomatic residences in cities with high PM$_{2.5}$, with mitigation, and for females of the same age living exclusively in the US

3.6 Sensitivity Analysis

The differences in DLL for the specified sensitivity analysis options were quantified by subtracting the DLL from the main model reported above: the differences in DLL ranged from -48.0 to + 55.1 for older diplomats, - 9.7 to +15.7 for young diplomats and -1.2 to +2.4 for children (Figure 7). Removing the inception lag had the largest impact on the DLL among the investigated model variations for older diplomats (+55.2 (+68%) DLL male, +36.4 (+76%) DLL female) and younger diplomats (+15.7 (+151%) DLL male, +9.4 (+90%) DLL female). Using the upper CI of the C-R function also resulted in an increase in DLL both among older diplomats (+22.5 (+28%) DLL male, +15.6 (+33%) DLL female) and young diplomats (+12.0 (+115%) DLL male, +7.3 (+70%) DLL female). Using the short lag on COPD and LRI and, separately, the long lag on lung cancer, both had small impacts on the DLL for older and young diplomats. Model variations applied to older diplomats resulted in a decrease in DLL: removing lags from the model (-16.3 (-20%) DLL male, -13.9 (-29%) DLL female), using the minimum C-R function (-17.1 (-21%) DLL male, -14.2 (-30%) DLL female), using high income mortality rates (-28.2 (-35%) DLL male and female) and removing the cessation lag (-48.0 (-59%) DLL male, -34.0 (-71%) DLL female). Application of the short lag to COPD and LRI suggested the largest possible impacts on DLL for children (+2.9 (+431%) DLL male, female +1.8 (+465%) DLL female). All other model variations resulted in less than 1 DLL gained or lost. Use of high income US baseline mortality statistics, instead of mortality statistics for the entire US population, resulted in a slight gain in DLL (+0.7 (+103%) DLL male, (+0.4 (+95%) DLL female) as did removal of the cessation lag for all six pollution sensitive conditions (+0.7 (+100%) DLL male, +0.5 (+100%) DLL female). Use of the 20-year inception and cessation lags yielded results that were roughly midway between the results when other elements of the model were changed.

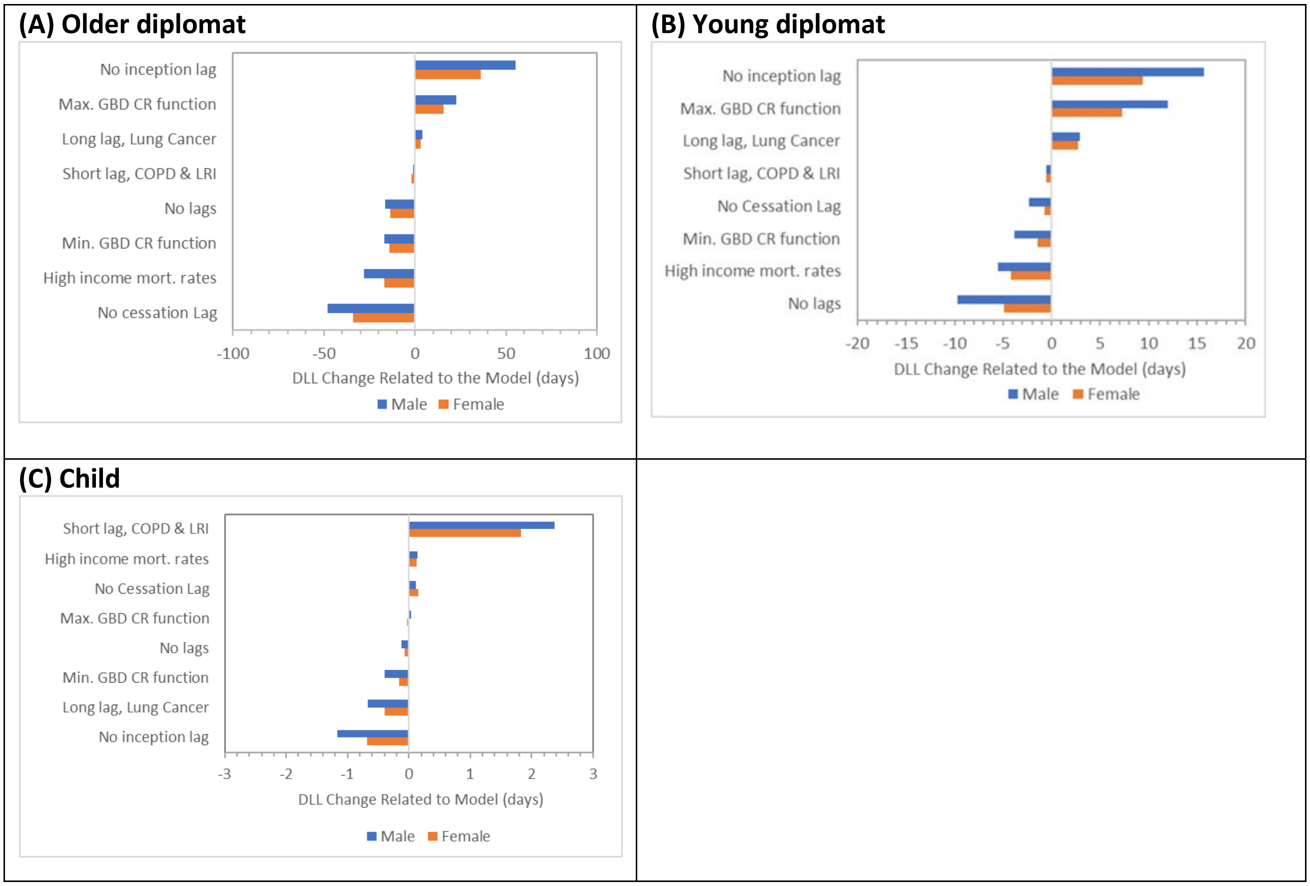


Figure 7: Change in the days of life lost (DLL) from the main model for each sensitivity analyses option: for an (A) older diplomat (B) younger diplomat and (C) child of a diplomat.

4.0 Discussion

We developed a novel approach to estimate the impact on mortality due to local $PM_{2.5}$ concentrations given assignments with frequent relocations to areas of varying $PM_{2.5}$. A set of systematically designed 20-year diplomatic assignments were used to demonstrate the impacts of the assignment patterns of city-specific annual mean $PM_{2.5}$ on the health of US diplomats. Key findings include that age at the time of relocation is critically important in determining the impact of air pollution on mortality, with greater impacts found for relocations amongst older diplomats than for young diplomats or the child of a diplomat (due to greater underlying mortality rates in older age groups). The mortality impacts decreased when assignments in high $PM_{2.5}$ cities were followed by assignments in low $PM_{2.5}$ cities and using room APs and improving home airtightness in polluted cities may have the potential to reduce the impacts considerably. According to the sensitivity analysis, the estimated health impacts were more sensitive to the choice of inception and cessation lags than to the $PM_{2.5}$ exposure level, C-R functions, or baseline mortality. Removal of the inception lag increased the DLL by 68% and 76% for male and female older diplomats compared to the original model including both lags, while removal of the cessation lag reduced the DLL by 59% and 71%.

This study demonstrated a new indirect method using WHO air quality data and GBD C-R functions to quantify the lifetime health impacts of air pollution exposure that frequently changes for a highly mobile population with relocations between global cities. There are several notable features in the model. The model uses US national mortality rates by sex and 1 year age groups and baseline mortality using the life table analysis which enables the calculation of life expectancy and days of life lost, considering the time when death occurs during the life course. This adds value to estimates based on the number of deaths which are commonly reported by previous quantitative risk assessments such as the GBD study (GBD Risk Factors Collaborators, 2020b). The model enables incorporation of multiple inception and cessation lags for targeted health outcomes, applied when diplomats relocate to an area with a change in ambient $PM_{2.5}$. The model allows for examining the impact of mitigation on life expectancy and days of life lost, based on prior research on mitigation used by US diplomats in Kathmandu

(Edwards et al., 2023). The model would benefit from a closer exploration and understanding of historical $PM_{2.5}$ trends in cities that host a US Embassy as fixed-site ambient $PM_{2.5}$ monitoring data is not available in many LMICs.

Our exploratory study also has several limitations and methodological challenges. First, there was limited availability of annual mean $PM_{2.5}$ data for cities used in the assignment scenarios, particularly for years prior to 2010. The use of $PM_{2.5}$ annual mean data from several years before or after the year of interest may result in misclassification of exposure. This could underestimate the exposure in many cities because $PM_{2.5}$ was generally higher in earlier years when it was not commonly measured. Future applications of the model would therefore benefit from incorporating consistent ambient $PM_{2.5}$ monitoring data collected across global cities, particularly in LMICs. However, in this study the accuracy of the $PM_{2.5}$ data is a lesser concern as the purpose of this study was to demonstrate changes in mortality associated with illustrative variations in $PM_{2.5}$ levels and not to directly attribute it to time spent in any particular city. Second, the model did not consider the different, but highly uncertain, nature of $PM_{2.5}$ sources in each global location and the impact that $PM_{2.5}$ from different sources may have on mortality (Chowdhury et al., 2022). Indeed, our study included cities where the majority of $PM_{2.5}$ can be attributed to emissions from soils, plants, and dust (Riyadh and Dakar) and cities with high levels of $PM_{2.5}$ due to burning biofuels for domestic energy use (Bangkok and Kathmandu). The exposure levels vary among the US diplomatic corps and their family members as evidenced in prior research among this population in Kathmandu (Edwards et al., 2023). The model explored the impact of enhanced mitigation in the workplace and at home as previously described by Edwards *et al*. Third, using estimates of city-wide $PM_{2.5}$ exposure may not provide an accurate representation of exposure for diplomats as they may spend more time in less polluted areas in the city as well as using APs in their workplace and homes. Fourth, our model may underestimate impacts in children because GBD 2019 C-R functions for IHD and stroke were only available for persons aged 25 years and above and we did not apply additional risks to persons under 25. It is expected that $PM_{2.5}$ related IHD, and stroke risks are likely to be marginal for persons under 25. It should also be noted that our model included only mortality and the effects of air pollution on children may be more pronounced in terms of morbidity, such as exacerbation of asthma. Fifth, we used baseline mortality risks for the US general population to represent the baseline mortality risks for US diplomats which may not be entirely representative for diplomats' health conditions, as diplomats are likely to be healthier than the general population due to better nutrition and increased access to medical care. In order to address this issue, we explored the effects of limiting the baseline mortality rates to those with higher socioeconomic status (SES) in the sensitivity analysis. However, C-R functions might also be different for the higher SES population as modification of $PM_{2.5}$ effects on mortality by SES is very often observed in cohort studies (Christidis et al., 2019; Keidel et al., 2019). Sixth, the set of 10 illustrative assignments used in this study does not cover the wide range of realistic assignment patterns for US diplomats. Application of this model to a greater number of assignments using actual human resources data for US diplomats would provide realistic total mortality burdens among the US diplomatic population. Seventh, the use of mitigation activities including APs at home and improved home tightness in cities with high $PM_{2.5}$ assumed a 50% reduction in $PM_{2.5}$ exposure in those cities, based on results of our previous Kathmandu study (Edwards et al., 2023). As the reduction of the outdoor $PM_{2.5}$ level depends on the housing structure in each local setting in a different city, this is a very rough estimate and a universal assumption applied to a range of cities. While the results associated with mitigation suggested beneficial effects for all age groups, the reported DLLs should be interpreted with caution. Nonetheless, this example illustrates the possible health benefits, in terms of the reduction of DLLs, through the use of mitigation at home and in the workplace in highly polluted cities.

Very few prior studies are directly comparable to the modeling strategy proposed here. A study conducted among US military families who experienced frequent relocations within the US reported that respiratory hospitalizations among children aged 2-5 years increased among those living in cities with high ozone (O_3) levels, although the study suffered from limited power when the analysis was confined to movers (Lleras-Muney, 2010). The study focused on US domestic relocations and did not involve dramatic changes in air pollution exposure. Several studies have quantified the health impacts of mitigation measures to reduce air pollution exposure. A UK modeling study found that lifetime use of APs at home may increase life expectancy by 138 and 120 days or more for males and females, respectively (Cooper et al., 2022). Like ours, the study used life table methods and GBD C-R functions for IHD, stroke, COPD, LRI and lung cancer, although neither inception nor cessation lags were applied in the model, which is less crucial for minimal changes in exposure. A US modeling study evaluated the mortality-related benefits and costs of improvements in particle filtration in US homes and commercial buildings accounting for time spent in various environments as well as activity levels and associated breathing rates. The results indicated that the use of portable APs in homes in the US could be a cost-effective strategy to reduce particle-related mortality (Fisk & Chan, 2017). While our results with mitigation measures were encouraging, the model did not address any detrimental effects of improved home airtightness, including possibly increased indoor $PM_{2.5}$, carbon dioxide and other indoor pollutants (Kelly & Fussell, 2019; Mannan & Al-Ghamdi, 2021).

The findings from this study provide useful information to support decision making to reduce health risks for people with frequent international relocations including the diplomatic corps and other professional groups whose $PM_{2.5}$-related mortality risk and life expectancy may be affected by overseas assignments. Our results suggest that, where possible, hiring agencies and employees may want to consider scheduling work in cities with high $PM_{2.5}$ at the beginning of the career rather than at older ages, when baseline mortality rates increase steeply with age. After completion of a posting in a city with high $PM_{2.5}$, hiring agencies and employees may also want to request that their next posting be in a city with low $PM_{2.5}$, if possible. It should be noted that there are many important factors in determining staffing assignments including the suitability for available positions, amount of training and expertise needed in various positions, as well as other personal and family health and safety considerations. Although ambient $PM_{2.5}$ could impact diplomats' health, it is only one of many important factors that employers may want to consider when determining global staffing assignments and the duration of assignments. Our previous study in Kathmandu suggested that the use of high capacity air purifiers and improvement of building airtightness greatly reduced $PM_{2.5}$ personal exposure (Edwards et al., 2023). The application in this model of an indicative reduction rate of $PM_{2.5}$ exposure from the Kathmandu study suggested that potential health benefits could be achieved from these mitigation measures. In reality, there are inequalities in access to such expensive mitigation measures across the globe, especially in LMICs. In addition, the use of air purifiers may not be an ideal solution given concerns about climate change and planetary health. Additional research is needed to identify the most appropriate options for mitigation in public buildings and residences in LMICs and with some modifications, this model could be applied to local citizens in LMICs to examine how their life expectancy may change following introduction of exposure mitigation activities.

5.0 Conclusions

We developed a novel health impact model to estimate the effect of lifetime exposure to changing $PM_{2.5}$ levels on mortality for individuals with regular international relocations, by applying published C-R functions with inception and cessation lags. The application of the model to US diplomats in various assignments suggested that an increased number of years living in high $PM_{2.5}$ cities resulted in an elevated mortality risk, with greater health impacts in older diplomats than young diplomats or their children because of their greater underlying mortality rates for conditions sensitive to air pollution. Alternating assignments, when possible spending a few years in a high $PM_{2.5}$ city followed by a year or more in a city with a lower $PM_{2.5}$ concentration may help to reduce the additional risk of mortality due to $PM_{2.5}$. Our results also suggest that the use of air purifiers and improved home airtightness may help mitigate health burdens due to exposure to ambient $PM_{2.5}$. The choice of inception and cessation lags is critical for the magnitude of the estimated mortality burdens and, as such, further research on the delayed effects of $PM_{2.5}$ exposure on cause-specific mortality is required to improve model estimates.

References

Awad, Y. A., Di, Q., Wang, Y., Choirat, C., Coull, B. A., Zanobetti, A., & Schwartz, J. (2019). Change in PM2.5 exposure and mortality among Medicare recipients: Combining a semi-randomized approach and inverse probability weights in a low exposure population. Environmental Epidemiology, 3(4), e054.

Barkjohn, K. K., Norris, C., Cui, X., Fang, L., Zheng, T., Schauer, J. J., . . . Bergin, M. H. (2021). Real-time measurements of PM2.5 and ozone to assess the effectiveness of residential indoor air filtration in Shanghai homes. Indoor Air, 31(1), 74-87. doi:10.1111/ina.12716

Ben-Shlomo, Y., Smith, G. D., Shipley, M. J., & Marmot, M. G. (1994). What determines mortality risk in male former cigarette smokers? American Journal of Public Health, 84(8), 1235-1242. doi:10.2105/ajph.84.8.1235

Centers for Disease Control and Prevention. (2021). National Vital Statistics System, Mortality 1999-2020 on CDC WONDER Online Database (Publication no. http://wonder.cdc.gov/ucd-icd10.html). Retrieved May 19, 2022 http://wonder.cdc.gov/ucd-icd10.html

Chen, J., & Hoek, G. (2020). Long-term exposure to PM and all-cause and cause-specific mortality: A systematic review and meta-analysis. Environment International, 143, 105974. doi:10.1016/j.envint.2020.105974

Chowdhury, S., Pozzer, A., Haines, A., Klingmuller, K., Munzel, T., Paasonen, P., . . . Lelieveld, J. (2022). Global health burden of ambient PM(2.5) and the contribution of anthropogenic black carbon and organic aerosols. Environment International, 159, 107020. doi:10.1016/j.envint.2021.107020

Christidis, T., Erickson, A. C., Pappin, A. J., Crouse, D. L., Pinault, L. L., Weichenthal, S. A., . . . Brauer, M. (2019). Low concentrations of fine particle air pollution and mortality in the Canadian Community Health Survey cohort. Environmental Health: A Global Access Science Source, 18(1), 84. doi:10.1186/s12940-019-0518-y

Clancy, L., Goodman, P., Sinclair, H., & Dockery, D. W. (2002). Effect of air-pollution control on death rates in Dublin, Ireland: an intervention study. Lancet, 360(9341), 1210-1214. doi:10.1016/S0140-6736(02)11281-5

Cohen, A. J., Brauer, M., Burnett, R., Anderson, H. R., Frostad, J., Estep, K., . . . Forouzanfar, M. H. (2017). Estimates and 25-year trends of the global burden of disease attributable to ambient air pollution: an analysis of data from the Global

Burden of Diseases Study 2015. Lancet, 389(10082), 1907-1918. doi:10.1016/S0140-6736(17)30505-6

Cooper, E., Milner, J., Wang, Y., Stamp, S., & Mumovic, D. (2022). Modelling the impact on mortality of using portable air purifiers in UK homes. Atmospheric Environment, 289. doi:https://doi.org/10.1016/j.atmosenv.2022.119311

Edwards, L., Wilkinson, P., Rutter, G., & Milojevic, A. (2022). Health effects in people relocating between environments of differing ambient air pollution concentrations: A literature review. Environmental Pollution, 292(Pt A), 118314. doi:10.1016/j.envpol.2021.118314

Edwards L., Wilkinson, P., Rutter, G., Iverson, L., & Milojevic, A. (2023). Impact of mitigation measures to improve home indoor air quality in Kathmandu, Nepal. Environmental Research: Health, 1. doi:https://doi.org/10.1088/2752-5309/acb663

Fisk, W. J., & Chan, W. R. (2017). Effectiveness and cost of reducing particle-related mortality with particle filtration. Indoor Air, 27(5), 909-920. doi:10.1111/ina.12371

Fuller, R., Landrigan, P. J., Balakrishnan, K., Bathan, G., Bose-O'Reilly, S., Brauer, M., . . . Yan, C. (2022). Pollution and health: a progress update. The lancet. Planetary Health, 6(6), e535-e547. doi:10.1016/S2542-5196(22)00090-0

Gan, W. Q., Tamburic, L., Davies, H. W., Demers, P. A., Koehoorn, M., & Brauer, M. (2010). Changes in residential proximity to road traffic and the risk of death from coronary heart disease. Epidemiology, 21(5), 642-649. doi:https://dx.doi.org/10.1097/EDE.0b013e3181e89f19

GBD Risk Factors Collaborators. (2020). Global burden of 87 risk factors in 204 countries and territories, 1990-2019: a systematic analysis for the Global Burden of Disease Study 2019. Lancet, 396(10258), 1223-1249. doi:10.1016/S0140-6736(20)30752-2

Health Effects Institute. (2020). State of Global Air 2020. Retrieved from www.stateofglobalair.org

Health Effects Institute. (2022). Systematic Review and Meta-analysis of Selected Health Effects of Long-Term Exposure to Traffic-Related Air Pollution. Retrieved from https://www.healtheffects.org/publication/systematic-review-and-meta-analysis-selected-health-effects-long-term-exposure-traffic

Keidel, D., Anto, J. M., Basagana, X., Bono, R., Burte, E., Carsin, A. E., . . . Probst-Hensch, N. (2019). The Role of Socioeconomic Status in the Association of Lung Function and Air Pollution-A Pooled Analysis of Three Adult ESCAPE Cohorts. International Journal of Environmental Research & Public Health [Electronic Resource], 16(11). doi:10.3390/ijerph16111901

Kelly, F., & Fussell, J. C. (2019). Improving indoor air quality, health, and performance within environments where people live, travel, learn and work. Atmospheric Environment, 200, 90-109. doi:https://www.sciencedirect.com/science/article/pii/S1352231018308410

Kenfield, S. A., Wei, E. K., Stampfer, M. J., Rosner, B. A., & Colditz, G. A. (2008). Comparison of aspects of smoking among the four histological types of lung cancer. Tobacco Control, 17(3), 198-204. doi:10.1136/tc.2007.022582

Knoke, J. D., Burns, D. M., & Thun, M. J. (2008). The change in excess risk of lung cancer attributable to smoking following smoking cessation: an examination of different analytic approaches using CPS-I data. Cancer Causes Control, 19(2), 207-219. doi:10.1007/s10552-007-9086-5

Krewski, D., Burnett, R. T., Goldberg, M. S., Hoover, B. K., Siemiatycki, J., Jerrett, M., . . . White, W. H. (2003). Overview of the reanalysis of the Harvard Six Cities Study and American Cancer Society Study of Particulate Air Pollution and Mortality. Journal of Toxicology & Environmental Health Part A, 66(16-19), 1507-1551. doi:10.1080/15287390306424

Laden, F., Schwartz, J., Speizer, F. E., & Dockery, D. W. (2006). Reduction in fine particulate air pollution and mortality: Extended follow-up of the Harvard Six Cities study. American Journal of Respiratory & Critical Care Medicine, 173(6), 667-672. doi:10.1164/rccm.200503-443OC

Leavitt, M. (2004). Advisory Council on Clean Air Compliance Analysis Response to Agency Request on Cessation Lag. Retrieved from https://nepis.epa.gov

Leksell, I., & Rabl, A. (2001). Air pollution and mortality: quantification and valuation of years of life lost. Risk Analysis, 21(5), 843-857. doi:10.1111/0272-4332.215156

Lleras-Muney, A. (2010). The Needs of the Army: Using Compulsory Relocation in the Military to Estimate the Effect of Air Pollutants on Children’s Health. Journal of Human Resources, 45. doi:10.1353/jhr.2010.0016

Mannan, M., & Al-Ghamdi, S. G. (2021). Indoor Air Quality in Buildings: A Comprehensive Review on the Factors Influencing Air Pollution in Residential and Commercial Structure. International Journal of Environmental Research & Public Health [Electronic Resource], 18(6). doi:10.3390/ijerph18063276

Meng, J., Li, C., Martin, R. V., van Donkelaar, A., Hystad, P., & Brauer, M. (2019). Estimated Long-Term (1981-2016) Concentrations of Ambient Fine Particulate Matter across North America from Chemical Transport Modeling, Satellite Remote Sensing, and Ground-Based Measurements. Environmental Science & Technology, 53(9), 5071-5079. doi:10.1021/acs.est.8b06875

Miller, B. G., & Hurley, J. F. (2003). Life table methods for quantitative impact assessments in chronic mortality. Journal of Epidemiology & Community Health, 57(3), 200-206. doi:10.1136/jech.57.3.200

Pope, C. A., 3rd, Coleman, N., Pond, Z. A., & Burnett, R. T. (2020). Fine particulate air pollution and human mortality: 25+ years of cohort studies. Environ Res, 183, 108924. doi:10.1016/j.envres.2019.108924

U.S. Environmental Protection Agency. (2004). Advisory Council on Clean Air Compliance Analysis Response to Agency Request on Cessation Lag.

United States Census Bureau. (2021). American Community Survey 5-Year Data (2009-2021) (Publication no. https://www.census.gov/data/developers/data-sets/acs-5year.html).

United States Department of State. (2018). Survey data from posts, unpublished data.

United States Department of State. (2022). Foreign Affairs Manual.

US Environmental Protection Agency. (2018). Air Quality Trends (2001-2018).

Walton, H. (2010). Supporting paper to COMEAP 2010 report The Mortality Effects of Long-Term Exposure to Particulate Air Pollution in the United Kingdom. Retrieved from https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/304655/COMEAP_development_of_proposals_for_cessation_lags.pdf

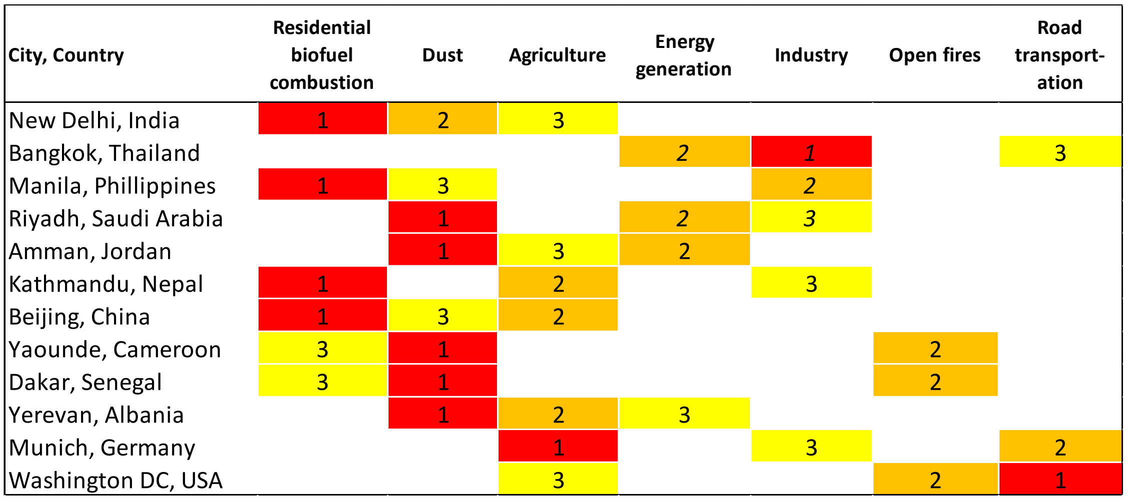
World Health Organization. (2022). Air quality database. Retrieved from https://www.who.int/data/gho/data/themes/air-pollution/who-air-quality-database

6.3 Postscript to research paper

My independent contributions to this paper include (1) constructing and building the health model used in the analysis, (2) identifying and obtaining US baseline mortality statistics by one year age intervals and sex that were incorporated into the model, (3) development of the ten 20-year assignment profiles following interviews with career US diplomats regarding their respective assignment histories, (4) conducting the data analysis, (5) writing the first draft of the manuscript, (6) incorporating advice from co-authors into subsequent drafts of the manuscript, (7) preparing all tables and figures included in the manuscript, (8) submitting the manuscript and related materials to the journal *Environmental Health* for consideration. Further details about my contributions to the research are available on the Research Paper Cover Sheet (Item D) included in Section 6.2 of my thesis.

Sources of $PM_{2.5}$ vary globally and a review of the limited literature available suggests that the $PM_{2.5}$ source may have an impact on health outcomes associated with $PM_{2.5}$ exposure (Hopke et al., 2020; Karagulian et al., 2015; Kim et al., 2022; Liu et al., 2023; Mu et al., 2023). The health model developed in this study did not consider the respective source attribution for ambient $PM_{2.5}$. The literature was explored to identify sources of $PM_{2.5}$ in each of the cities included in diplomats' assignments used in the health model. Residential biofuel combustion is the leading contributor to ambient $PM_{2.5}$ in New Delhi, Manila, Kathmandu, and Beijing (McDuffie et al., 2021). Dust (anthropogenic, fugitive, combustion, industrial and windblown) is the leading contributor to ambient $PM_{2.5}$ in Riyadh, Amman, Yaounde, Dakar and Yerevan. This contrasts with $PM_{2.5}$ source attribution for the US which is led by road transportation, followed by open fires and agriculture. Figure 8 includes the top three contributors to ambient $PM_{2.5}$ in each of the cities included in the health model discussed in this chapter. Residential biofuel combustion and dust were the primary sources of $PM_{2.5}$ for a majority of the cities included in the ten illustrative diplomatic assignment profiles in the manuscript. $PM_{2.5}$ source apportionment information should be considered for further model development as the $PM_{2.5}$ composition has a direct bearing on the $PM_{2.5}$ related health effects, with $PM_{2.5}$ due to open fires and road transportation suspected to have greater toxicity than other sources of $PM_{2.5}$ (Aguilera et al., 2021; Park et al., 2018).

Figure 8: Top three source contributors to ambient $PM_{2.5}$ in locations used in the life table model



City, Country	**Residential biofuel combustion**	**Dust**	**Agriculture**	**Energy generation**	**Industry**	**Open fires**	**Road transport-ation**
New Delhi, India	1	2	3				
Bangkok, Thailand				*2*	*1*		3
Manila, Phillippines	1	3			*2*		
Riyadh, Saudi Arabia		1		*2*	*3*		
Amman, Jordan		1	3	2			
Kathmandu, Nepal	1		2		3		
Beijing, China	1	3	2				
Yaounde, Cameroon	3	1				2	
Dakar, Senegal	3	1				2	
Yerevan, Albania		1	2	3			
Munich, Germany			1		3		2
Washington DC, USA			3			2	1

The leading contributor to ambient $PM_{2.5}$ is indicated in red with the number "1", while the second and third contributors are represented in orange and yellow and indicated with the numbers "2" and "3".

The lifespan for older diplomats, young diplomats and children was constructed to include the 20-year diplomatic career period from 2001 to 2020 as this period has more data on ambient $PM_{2.5}$ in various countries that any period prior to 2001. The older diplomat began their 20-year diplomatic career at age 46 and ended at age 65, the year of mandatory retirement for diplomats in the US. In order for the diplomat to be 46 years old in 2001, the older diplomat would have been born in 1955. Likewise, the young diplomat began their 20-year diplomatic career at age 26 years old in 2001 and this diplomat was born in 1975. Finally, the child of a diplomat began their 20-year period of accompanying their parent(s) on diplomatic assignments at birth in 2001.

Health screenings for diplomats and their accompanying family members could impact the mortality estimates produced by this model. Diplomats and their family members who are moving to an international location must undergo a rigorous medical clearance process before each international relocation. Diplomats may not be medically cleared for an international relocation if they, or their accompanying family member, have a medical condition that cannot be managed safely while living in a particular international location. Medical clearance for a person to relocate to a city with high ambient $PM_{2.5}$ may be denied if the person has a history of cardiovascular or chronic respiratory conditions that may be exacerbated by $PM_{2.5}$. Medical clearance could also be denied if the person requires management by a medical specialist and there are no medical professionals with that specialty in the new location, for example, a diplomat who had a history of cerebrovascular accidents, or strokes, would be denied medical clearance to relocate to a city that did not have any licensed neurologists. This level of health screening during medical clearance results in persons with more severe medical conditions being confined to work in Washington, D.C., or another US location. Given that, in many cases, diplomats and their family members with a history of medical conditions that are exacerbated by $PM_{2.5}$ are blocked from relocating to a location with high ambient $PM_{2.5}$, this may impact the health model by overestimating the $PM_{2.5}$-related mortality for the diplomatic population as the GBD $PM_{2.5}$ integrated exposure response functions were based on the general population, not on a population with the highest risk members excluded.

GBD 2019 concentration-response (C-R) functions for six causes of mortality, IHD, stroke, COPD, LRI, type 2 diabetes mellitus, and lung cancer, were used in the health model to help quantify the $PM_{2.5}$-related mortality risk based on the ambient $PM_{2.5}$ in each city during the diplomat's lifespan (GBD Risk Factors Collaborators, 2020b). GBD 2019 C-R functions were developed by using meta-regression-Bayesian regularized trimmed (MRBRT) model and included a wider body of evidence in the C-R function development including findings from studies of exposure to very high ambient $PM_{2.5}$ levels, household air pollution, and secondhand smoke (GBD Risk Factors Collaborators, 2020b; Pozzer et al., 2023). The MRBRT built upon the Global Exposure Mortality Model (GEMM) used in the GBD 2017 analysis, which included findings from studies of long term exposure to ambient $PM_{2.5}$ and excess mortality, and the GEMM C-R functions were developed for all noncommunicable disease plus acute LRIs (Burnett et al., 2014). Other risk functions developed to quantify the relationship between $PM_{2.5}$ and health outcomes include a log linear C-R function to quantify the risk of mortality due to lung cancer, cardiopulmonary disease and all-cause mortality following long-term exposure to $PM_{2.5}$ in the American Cancer Society's Cancer Prevention II study in the US (Pope et al., 2002). Pope *et al.* reported an 8%, 6% and 4% increase in mortality due to lung cancer, cardiopulmonary disease and all-causes per 10 $\mu g/m^3$ in $PM_{2.5}$. The initial GBD study used a log C-R function which was based on ambient PM_{10} data reported in 304 cities that typically reported relative low levels of ambient PM_{10} and/or $PM_{2.5}$ (less than 35 $\mu g/m^3$) (Cohen et al., 2005). In many locations, $PM_{2.5}$ was calculated based on ambient PM_{10} measured data. Cohen *et al.* reported that $PM_{2.5}$ caused 3% of cardiopulmonary disease mortality, 5% of trachea, bronchus, and lung cancer mortality and 1% of acute respiratory infection mortality among children under 5 years of age. Other risk estimates described in the literature were considered for the health model, including the C-R function endorsed by COMEAP, RR 1.08 (95% CI: 1.06, 1.09) for natural cause mortality per 10 $\mu g/m^3$ ambient $PM_{2.5}$ (Committee on the Medical Effects of Air Pollutants, 2022). This C-R function was based on the findings in a systematic review conducted by Chen *et al.* that followed WHO methodology and based primarily on cohort studies conducted in North America and Europe (Chen & Hoek, 2020). Pope *et al.* conducted a systematic review of US cohort studies with a meta-analysis that yielded hazard ratios of 1.12 (95% CI: 1.08, 1.15) for all-cause mortality, 1.23 (95% CI: 1.17-1.29) for cardiopulmonary mortality and 1.12 (95% CI: 1.0, 1.26) for lung cancer mortality, all per 10 $\mu g/m^3$ ambient $PM_{2.5}$ (Pope et al., 2020). The exposure response functions generated by the meta-analyses by Chen and Pope were not selected due to the limited geographic area from which the studies included in the systematic reviews were conducted. Ultimately the C-R functions used in the GBD 2019 analysis were employed in my health model due to the increased availability and usage of global long-term studies used in development of this risk function. GBD 2019 C-R functions were selected for the risk estimate for my health model since they were based on findings from global research activities, as opposed to being generated through research conducted in a single country and C-R functions were defined separately for six causes of mortality. The GBD C-R functions take into consideration the variability of RR associated with differing levels of $PM_{2.5}$ including a flattening or plateau at very high $PM_{2.5}$ levels.

6.4 Fulfillment of thesis objectives

The research presented in this chapter fulfilled objective 3, as the study described my development of a health impact model that quantified the mortality burden associated with $PM_{2.5}$ exposure among US diplomats and family members with multiple international assignments including highly polluted cities. The study revealed that $PM_{2.5}$-related mortality increased as the age of the diplomat increased and that alternating assignments in high and low $PM_{2.5}$ cities may help reduce $PM_{2.5}$-related mortality burdens. Adding exposure mitigation in diplomats' homes while working in highly polluted cities may help reduce $PM_{2.5}$-related mortality, as demonstrated by applying the fraction of personal to ambient $PM_{2.5}$ reduction observed in the intervention study in Kathmandu, described in Chapter 5.

PART III: Discussion

7 Discussion

7.1 Context of the thesis

My research presented in this thesis expanded upon the limited evidence available on the $PM_{2.5}$ exposure among US diplomats working in a city with high ambient $PM_{2.5}$ concentrations and on the health effects associated with varying $PM_{2.5}$ levels among a population with frequent relocations. Diplomats typically spend 2 to 4 years in each assignment to a city that host a US Embassy, Consulate, or other US government office and, depending on diplomats' work duties, language skills and preferences, they can spend 20 years living in cities with ambient $PM_{2.5}$ considerably higher than that in the United States. In many but not all highly polluted cities, diplomats are given air purifiers to use in their residences, but it has been unclear how much they can expect the $PM_{2.5}$ in their homes to improve when using the air purifiers.

While prior studies have identified changes in lung function among adolescents who relocated (Avol et al., 2001) and decreased systolic blood pressure and increased inflammatory biomarkers among young adults that experienced a short-term change in ambient $PM_{2.5}$ (Rich et al., 2012), no prior publications were identified that examined the change in health status among persons with changes in ambient $PM_{2.5}$ due to multiple residential relocations during their lifespan. Therefore, it was necessary to provide further evidence on the varying $PM_{2.5}$ levels and the exposure-related health impacts for US diplomats to better inform their assignment location requests and to help inform US government human resources experts' decision making when deciding diplomats' assignment locations.

I performed a systematic literature review to identify health status changes following a relocation to an area with an increase or decrease in ambient air pollution. Using a natural experiment study design, I examined diplomats' personal exposure to $PM_{2.5}$ and microenvironments associated with high $PM_{2.5}$ exposure in a city with high ambient $PM_{2.5}$ levels before and during COVID-19 pandemic lockdown. I conducted an intervention study to provide evidence as to diplomats' personal exposure to $PM_{2.5}$ in relation to ambient $PM_{2.5}$ levels in a highly polluted city and quantified the impact that enhanced mitigation had on personal exposure. Finally, I developed a novel model to estimate the impact that varying levels of $PM_{2.5}$ may have on the life expectancy of diplomats and their accompanying family members. The synthesis of the findings from the literature review, natural experiment, intervention study and health impact model add to the current knowledge and provide insights about the health effects of varying $PM_{2.5}$ levels among populations with frequent relocations, including US diplomats, and the potential impact that enhanced mitigation may have on mortality for diplomats and their accompanying family members.

Thesis chapters 3 to 6 include the research papers with discussion of findings, strengths and limitations described for each activity. The research in chapters 3 to 5 have been published while the paper in chapter 6 has been submitted to a journal for consideration.

7.2 Summary of PhD main findings

The main findings from the review chapter of the background and those of the results section are summarized here.

7.2.1 Chapter 3: Health effects in people relocating between environments of differing ambient air pollution concentrations: a literature review

Very limited literature was identified that described the health effects of air pollution among populations who have relocated, and the literature was very heterogenous in design and quality. Among 15 articles identified in the literature review, four studies were of short term (less than six months) relocation focused on lung function, blood pressure or biomarkers following short-term (less than six months) travel or relocation and broadly suggested short-term adverse effects of air pollutants. Among the eleven studies with a long-term (greater than or equal to six months) relocation, four indicated an increase in deleterious health effects including lung function, pediatric respiratory hospitalizations, and mortality after relocating to an area with an increase in air pollution.

My results indicate that relocation studies can be advantageous for epidemiological research. Many studies included in the review offered an opportunity to explore the relationship between a change in ambient air pollution and health outcomes with reduced confounding and relatively low risk of bias. Other studies included in the review provided evidence on the nature and timing of functional short-term effects of changes in air pollution exposure, which, although at probably high risk of bias, provide a useful adjunct to other epidemiological studies. Overall, most relocation studies are consistent with short- or long-term adverse effects of air pollution on biological function or mortality, but many studies of change in exposure have design weaknesses that limit the robustness of interpretation. My study suggests there would be value in expanding air pollution research that capitalizes on the advantages of relocation studies, but attention is needed to improve potential bias and confounder control in studies examining the effects of short-term relocations to environments of different air pollution levels.

7.2.2 Chapter 4: Personal exposure monitoring of $PM_{2.5}$ by US diplomats in Kathmandu during the COVID-19 lockdown, March-June 2020

US diplomats' personal exposure to $PM_{2.5}$ in indoor environments in Kathmandu during the COVID-19 lockdown was very low and time spent outdoors and at home, especially when cooking, were the largest contributors to personal exposure. Ambient $PM_{2.5}$ measured using ambient fixed-site monitors at the US Embassy and in Phora Durbar, a neighborhood where many diplomats live, during the 2020 COVID lockdown period was approximately 40% lower than during the corresponding period in 2017-2019. The four participants examined in this study had mean concentrations of $PM_{2.5}$ that were at least 50% lower than their own mean hourly concentration prior to lockdown and at least 83% less than the mean hourly ambient $PM_{2.5}$ measured at the US Embassy's fixed site monitor. Low indoor levels of $PM_{2.5}$ were achieved at work and home through the use of air purifiers and measures to seal homes against the ingress of polluted air from outside including sealing windows and doors with plastic sheeting, thick tape or caulk used around openings. My observations indicate the potential reduction in exposure to $PM_{2.5}$ following large-scale changes to fossil-fuel related emissions sources, through control of $PM_{2.5}$ in indoor environments and activity patterns including time spent outdoors.

Evidence presented in this Chapter showed appreciable reductions in both outdoor $PM_{2.5}$ levels and in personal exposure to $PM_{2.5}$ during the lockdown, with the reduction in personal exposure being due to altered activity patterns as well as to the reduced concentrations in various microenvironments. It also provides important evidence about the apparent effectiveness of indoor air filtration combined with anti-infiltration home sealing measures in reducing $PM_{2.5}$ in the home environment. COVID-19 restrictions in Kathmandu were associated with substantial reductions in ambient concentrations of $PM_{2.5}$ and with large reductions in the personal exposure to $PM_{2.5}$ of US diplomats, due to both altered activity patterns (with less outdoor activity during lockdown) and lower $PM_{2.5}$ concentrations in many microenvironments.

7.2.3 Chapter 5: Impact of mitigation measures to improve home indoor air quality in Kathmandu, Nepal

The ratio of personal $PM_{2.5}$ to outdoor $PM_{2.5}$ for US diplomats in Kathmandu was reduced by 50% when high capacity air purifiers and, in some cases, improved air tightness, were implemented in diplomats' homes. This study provides rare evidence about the combined effect of the use of high-capacity air purifiers and improving dwelling air tightness to limit personal exposure to fine particle pollution in a setting with poorly sealed, traditional dwellings and high outdoor $PM_{2.5}$ concentrations. The results suggest that such combined measures achieved a considerable reduction in the indoor to outdoor ratio of $PM_{2.5}$ concentrations, from 0.20 pre-intervention to 0.10 post-intervention in the homes of study participants. This indicates a high degree of protection in the home environment against exposure to $PM_{2.5}$ derived from polluted outdoor air. Personal monitoring in Kathmandu revealed that adding high-capacity air purifiers and improving the seal of the home to the ingress of outdoor air helped to reduce the indoor $PM_{2.5}$ level at home, even at outdoor $PM_{2.5}$ levels more than 8 times the WHO's maximum daily mean level of 15 $\mu g/m^3$. The I/O ratios decreased post-intervention during the winter when outdoor $PM_{2.5}$ was high. These findings confirm that in locations with high outdoor $PM_{2.5}$, it is possible to achieve low home $PM_{2.5}$ levels and very low I/O ratios in homes that utilize high-capacity air purifiers and enhanced air tightness.

The high-capacity air purifiers used in the study were expensive, more than $500 U.S. each at the time the study was performed, and the cost is likely a barrier for adoption in many homes in Nepal. Air purifiers with a high clean air delivery rate are especially helpful for homes occupied by US diplomats, which are typically older and with reported leaky gaps in windows and doorways. Study participants were highly educated and informed about the importance of using air purifiers in dwellings, which may mean their use of air purifiers was better than might be assumed for the general population. The total of the home air purifier capacity per hour of all air purifiers in participants' homes increased by nearly 70% post-intervention and findings from the study represent what could be achieved when people have access to a very high level of air purification at home. Unfortunately, most people living in highly polluted cities do not have access to as many air purifiers as the study participants.

7.2.4 Chapter 6: Health impacts of changing exposure to $PM_{2.5}$ for diplomats with multiple international relocations: modeling study

The novel model of mortality due to $PM_{2.5}$ for diplomats with frequent relocations suggested alternating multi-year assignments in high and low $PM_{2.5}$ cities may help reduce the $PM_{2.5}$-related mortality burden. The days of life lost due to $PM_{2.5}$ exposure for an illustrative standard 20-year assignment ranged from 0.3 days for diplomats' children to 84.1 days for older diplomats. The DLL decreased when assignments in high $PM_{2.5}$ cities were followed by assignments in low $PM_{2.5}$ cities: 162.5 DLL when spending 20 years in high $PM_{2.5}$ cities and 62.6 DLL when spending one of every four years (5 years total) in a high $PM_{2.5}$ city for older male diplomats. Use of air purifiers and improved home tightness in polluted cities may reduce the DLL due to $PM_{2.5}$ exposure by 50% or more. Results of the model were highly sensitive to lag assumptions: DLL increased by 68% when inception lags were removed from the model and decreased by 59% when cessation lags were removed from the model for older male diplomats. The application of the model to US diplomats in various assignments suggested that an increased number of years living in high $PM_{2.5}$ cities resulted in an elevated mortality risk with greater magnitude for older diplomats than young diplomats or their children because of their greater underlying mortality rates for conditions sensitive to air pollution. Alternating assignments, when possible, spending a few years in a high $PM_{2.5}$ city followed by a year or more in a city with lower $PM_{2.5}$ concentration may help reduce the additional risk of mortality due to $PM_{2.5}$.

7.2.5 Synthesis of results across review, empirical and health modeling chapters

In combination, my research findings provide information about the microenvironments that are important for diplomats' $PM_{2.5}$ personal exposure in a highly polluted city, the impact of enhanced mitigation in diplomats' residences on $PM_{2.5}$ personal exposure, and evidence about an increase in mortality linked to diplomatic assignments in cities with high $PM_{2.5}$. My findings highlight the importance of air pollution on diplomats' health and is a vital topic for the diplomatic corps to address given that 96% of US Embassies and US Consulates are located in cities whose annual $PM_{2.5}$ mean is greater than the WHO's Air Quality Guideline's standard (5 $\mu g/m^3$) (World Health Organization, 2021). Diplomats are a highly mobile population with relocations occurring on a regular basis and, as evidenced in the literature review, very few studies of the health effects among persons who relocated to an area with a change in ambient air pollution have been published. Use of air purifiers in residences and, in some cases, increasing the home seal proved to be effective to reduce diplomats' personal exposure to $PM_{2.5}$ in Kathmandu as described in Chapter 5 and the modeling study in Chapter 6 detailed the possible impacts on life expectancy that may occur for US diplomats and their accompanying family members. Use of mitigation in residences and completing assignments in highly polluted cities either at a younger age or alternating assignments in high and low $PM_{2.5}$ cities may help US diplomats reduce $PM_{2.5}$ related health impacts incurred during their diplomatic career.

My thesis provides important evidence to help understand which populations among the diplomatic corps, and among their accompanying family members, may be the most susceptible to $PM_{2.5}$ exposure incurred during diplomatic assignments. Findings presented in Chapter 3 indicate that adolescents living in cities with high $PM_{2.5}$ are at greater risk for $PM_{2.5}$ related decreases in lung growth and lung function (Avol et al., 2001). Diplomats and their accompanying family members with health conditions that may be exacerbated by $PM_{2.5}$ exposure including cardiovascular and respiratory diseases identified in Chapter 3 and with advanced age, as indicated by the health modeling study in Chapter 6, may be more susceptible to health effects associated with high $PM_{2.5}$ exposure. Although these populations have elevated $PM_{2.5}$ related mortality, the results of the intervention study in Kathmandu indicate that use of air purifiers and improved airtightness at home offer diplomats the opportunity to decrease their $PM_{2.5}$ exposure (and to potentially decrease their risk of $PM_{2.5}$ related mortality). US diplomats working in cities with high $PM_{2.5}$ can request air purifiers to use at home from the US Embassy or US Consulate where they are assigned, and diplomats can work with the Embassy Management Office to seal their home if leaky windows and doorways are identified. Regular use of these mitigation options may result in mortality risks for pollution sensitive conditions similar to those of an American of similar age and sex living exclusively in the US, as demonstrated in the modelling study.

A range of factors and activities that may increase diplomats' $PM_{2.5}$ exposure were highlighted through my research presented in Chapters 4 and 5. These include cooking-related exposures in the home, exposures occurred at work, school or other daytime activities, housing quality, and timing and duration of outdoor activities. Indoor air quality in diplomats' homes was the core focus of Chapters 5 as study participants spent a majority of their time at home. Reducing $PM_{2.5}$ in the home, including $PM_{2.5}$ generated while cooking, was demonstrated to be a crucial activity to lower $PM_{2.5}$ exposure for diplomats and their family members in Kathmandu. In many instances, $PM_{2.5}$ exposure during working hours for diplomats can be extremely low as the air is highly filtered in most US Embassy and US Consulate buildings. However, in some cities, US Embassy buildings, including annexes and ancillary buildings, are older with leaky windows and doorways with indoor air quality approximately the same as the ambient air quality. Diplomats working in these settings are at increased risk for $PM_{2.5}$ related health effects than their US diplomatic colleagues working in the same city in buildings with highly filtered air. Spouses and children of diplomats may also be at greater risk of $PM_{2.5}$ related health effects, as spouses are often spending time in markets and local businesses that do not have $PM_{2.5}$ mitigation in place. Children of US diplomats typically attend a private American School in the city, many of which do not have $PM_{2.5}$ mitigation such as air purifiers in place. Depending on the local climate, many American Schools were designed with open cafeterias, gymnasiums and other rooms allowing ventilation, and ambient $PM_{2.5}$, to permeate throughout the school. Children of US diplomats may have far higher personal exposure to $PM_{2.5}$ than their parents. It may be helpful for air quality scientists and buildings' experts to monitor $PM_{2.5}$ levels in American Schools and to identify strategies to lower ambient $PM_{2.5}$ in these schools. Findings in both Chapters 4 and 5 speak to the importance of ensuring air quality and low $PM_{2.5}$ inside buildings in order to help reduce $PM_{2.5}$ exposure and $PM_{2.5}$ related health outcomes.

Diplomats and their family members who work in cities with high ambient $PM_{2.5}$ may have increased mortality, and shortened lifespan, if they do not employ efforts to mitigate their exposure such as to use air purifiers in their diplomatic residences. The research presented in Chapter 6 estimated the amount of life lost in a standard 20-year diplomatic assignment ranged from 0.3 days for diplomats' children to 84.1 days for older diplomats. The reduction in lifespan increased as the age of the diplomat working in a highly polluted city increased, as demonstrated through the use of a range of 20-year diplomatic assignment profiles in the health model in Chapter 6. The research indicated very limited impacts on mortality for children accompanying their parents in highly polluted cities. My research suggests that diplomats may be able to eliminate any additional $PM_{2.5}$-related impacts on mortality expects while working in highly polluted cities through the use of high-capacity air purifiers in diplomatic residences, and this finding was demonstrated in Chapter 6 by incorporating the ratio of personal to ambient $PM_{2.5}$

identified in Chapter 5. These findings should provide encouragement and evidence for diplomats to consistently use air purifiers in their residences in order to help limit $PM_{2.5}$-related mortality impacts for themselves and their accompanying family members.

7.3 Strengths of the research and contributions of the PhD to the field

The strengths of each component of the research are discussed in the published papers (Chapters 3-5) and submitted manuscript (Chapter 6). The key strengths of the overall doctoral research will be discussed in greater detail in this section.

The main strength of the research is that a variety of methods and study designs were used to explore my research questions as to the health effects of varying air population levels on a highly mobile population. The literature review was performed following consultation with an LSHTM librarian to help ensure that I cast a wide net to include all available published findings of health status and ambient pollution before and after relocations. Although it was surprising to only find 15 published articles that fit the inclusion criteria for the literature review, the strongest evidence identified described the impact on mortality among persons that relocated to an area with an increase in $PM_{2.5}$ or activity associated with increased $PM_{2.5}$, such as increased traffic. These findings helped to influence my decision to include mortality as the focus of the health model described in Chapter 6.

Collection of information about $PM_{2.5}$ personal exposure in a highly polluted city is a strength of the research as it provided evidence about the relationship between daily activities, time in various microenvironments, and use of mitigation at home on $PM_{2.5}$ exposure. Key components of the methods for the natural experiment study of the activities and microenvironments associated with $PM_{2.5}$ personal exposure for US diplomats in Kathmandu include the efforts to recruit US diplomats and family members that lived in a variety of locations in Kathmandu. US diplomats were notified about the study by email and flyers about the study were posted in multiple locations in the US Embassy. Another key component of the $PM_{2.5}$ personal monitoring studies includes the use of APT Minima $PM_{2.5}$ personal exposure monitoring equipment with optical particle counter technology (Applied Particle Technology, 2020; Li, 2020) which were programmed to report $PM_{2.5}$ every 30 seconds while in use. Personal monitors with optical particle counting technology were chosen instead of monitors with gravimetric assessment technology, as this choice allowed for frequent time-dependent $PM_{2.5}$ reporting throughout the personal monitoring period which provided the opportunity for the analysis of microenvironment specific $PM_{2.5}$ readings and comparison of personal to ambient $PM_{2.5}$ values at various points during monitoring, as opposed to a comparison only for the entire monitoring period on the whole. Two methods were used to check the validity and accuracy of the personal monitoring data including periodic co-location of each of the APT Minima personal monitors next to the US Embassy's fixed-site ambient $PM_{2.5}$ monitor for short periods of side-by-side monitoring as well as permanent co-location of an APT Maxima stationary air quality monitor next to the US Embassy's fixed-site monitor in Phora Durbar, to track the sensor calibration for local ambient aerosols. The personal monitoring equipment also reported temperature every 30 seconds which, through close examination of $PM_{2.5}$ personal exposure data and ambient temperature data, assisted with properly identifying when study participants were indoors versus outdoors. Another strength of the methods used in the research in Chapters 4 and 5 include the use of ambient data collected at two U.S. Embassy fixed site outdoor air quality monitoring stations. Study participants' homes were within 1.8 miles (2.9 kilometers) of an outdoor fixed-site air quality monitor and $PM_{2.5}$ data from the outdoor monitor located closer to each participant's home was used as the data source for their ambient $PM_{2.5}$ in the analysis. The database of personal exposure monitoring measurements recorded in this study was updated to include the corresponding hourly mean of the fixed-site ambient $PM_{2.5}$ monitor closest to each study participants' home for each personal monitoring datapoint recorded. This allowed for a comparison of the personal $PM_{2.5}$ to ambient $PM_{2.5}$ concentrations reflecting the direct timing of each personal monitoring session. Study participants reported time-activity patterns for the periods of personal monitoring using a customized diary to record their location and activities such as cooking, commuting, and exercising outdoors. During each monitoring session study participants reported the number and type of air purifiers used in their homes and the air purifier settings used (low, medium, or high). They also completed a questionnaire about efforts to seal the home against the outdoor air and sources of air pollution inside the home. records of participants' air purifiers used at home were cross referenced with US Embassy records about the number and type of air purifiers provided to participants to help ensure the accuracy of the information used in the analysis.

Another strength of my research is the examination of the change in personal $PM_{2.5}$ to ambient $PM_{2.5}$ following the intervention of adding additional air purifiers and, in some cases, improved airtightness of the homes. Provision of air purifiers to diplomats for use in their personal residence is one of the leading strategies that the US government uses to help empower diplomats to reduce their $PM_{2.5}$ exposure and to reduce health impacts due to $PM_{2.5}$. The results of the intervention study provide evidence as to what the home indoor air quality and $PM_{2.5}$ personal exposure could be for a diplomat in a highly polluted city if they use a very high level of home mitigation. Personal $PM_{2.5}$ monitoring, while laborious, offers empirical evidence on the study population and the results can provide evidence to support the recommendation for diplomats to use air purifiers in their residences in cities with high $PM_{2.5}$. The selection of Kathmandu, Nepal as the setting for the personal monitoring study is a strength to my research as the setting provided the opportunity to examine $PM_{2.5}$ personal exposure and the impact of added home mitigation on personal exposure in a highly polluted city. Both the natural experiment during the COVID pandemic (Chapter 4) and the intervention study (Chapter 5) conducted in Kathmandu offered evidence as to the microenvironments and activities most closely associated with exposure to $PM_{2.5}$, the results of which may help guide diplomats and their family members to make informed decisions about the importance of using air purifiers in their residences.

A final strength of my research is the development of the health model which yielded estimates on the impacted life expectancy for diplomats. The assignment scenarios used in the manuscript allowed for comparison and contrast in mortality for diplomats of varying ages, sexes and duration years spent in cities with high $PM_{2.5}$. A novel method was developed to include and combine inception and cessation lags in the health model. Although lags have been used in prior research studies, often of short term air pollution exposure, the process I described in Chapter 6 for applying the lags, with lags frequently resetting themselves when diplomats move to an area with a change in ambient $PM_{2.5}$, was quite unique (Walton, 2010). Ambient $PM_{2.5}$ data reported by the WHO was determined to be the best data source available for locations included in the ten diplomatic assignment scenario profiles, given the WHO's efforts to collect and verify the data by location and temporal variation. For time spent in the US, annual mean $PM_{2.5}$ levels reported by the US Environmental Protection Agency were used for years 1999 to 2021 and modeled data was used for US locations for years prior to 1999 (Meng et al., 2019; United States Environmental Protection Agency, 2018). The modeling study included step by step instructions describing how the inception and cessation lags were applied, which may provide a template for future modeling studies of the health effects of changes in air pollution exposure. The health model built upon the findings described in Chapter 5 and allowed for a comparison of the mortality in one assignment scenario with and without the use of a high level of mitigation in diplomats' homes while working in high $PM_{2.5}$ cities. The health modeling study provides an estimate of $PM_{2.5}$ related mortality for diplomats, and this information is not directly measured by the US government as neither long-term health studies of the US diplomatic corps nor monitoring of diplomats' mortality after retirement from the US government are in place. Using the combination of methods described in Chapters 3, 4, 5 and 6 enabled me to study a unique population who have frequent required relocations, drastic changes in $PM_{2.5}$ exposure levels and are highly mobile. Very limited research had previously been conducted on highly mobile populations and this research helps to reduce the knowledge gap about this topic. The setting for this research offers several opportunities to reduce exposure including modification of air filtration in the workplace and at home and improved air tightness in the residence. Diplomats are an understudied population with few published articles describing the health risks and related health outcomes among this highly mobile population.

7.4 Limitations of the thesis

Detailed potential limitations of the individual research components of this thesis are discussed within the results chapters (i.e., Chapters 3-6). In this section, I will discuss the most important limitations to consider when interpreting the overall results.

The first limitation of my thesis relates to change in the $PM_{2.5}$ personal monitoring study in Kathmandu described in Chapter 5. The COVID-19 pandemic had a considerable impact on my research activities and forced me to end the Kathmandu personal monitoring study five months early and to eliminate the planned personal monitoring study in Pristina, Kosovo. More than half of the enrolled study participants in Kathmandu were evacuated back to the United States in March 2020 and ceased participation in the Kathmandu-based study. Although the study that I originally planned ended early, I am grateful to have had the opportunity to add the natural experiment that examined how $PM_{2.5}$ personal exposure and time in microenvironments changed for US diplomats in Kathmandu before and during COVID-related lockdown in Kathmandu (Chapter 4). The study yielded valuable information for the US diplomatic population remaining in Kathmandu and for other US diplomats living in cities with high $PM_{2.5}$ to help guide behaviors to reduce personal exposure to $PM_{2.5}$ during the COVID-19 pandemic, when many diplomats were working in their diplomatic residences, and not working in the US Embassy. When the Kathmandu personal monitoring study ended before completion of a full year of data collection, I was forced to explore the data and consider other opportunities for research that could be completed using the data I had collected. I shifted my PhD aims and objectives to include an exploration of the impact of added high-capacity air purifiers and, in some cases, improved home airtightness, on the indoor $PM_{2.5}$ concentration in diplomats' homes and in the relationship between the personal $PM_{2.5}$ and ambient $PM_{2.5}$ before and after the addition of enhanced mitigation in diplomats' homes. Among the 30 diplomats and family members enrolled in the study, 22 had at least one $PM_{2.5}$ personal monitoring session conducted before and after the new high-capacity air purifiers were implemented in diplomats' residences. The findings from the intervention study helped to highlight the impact of enhanced mitigation in homes including reducing the ratio of the $PM_{2.5}$ personal exposure to ambient $PM_{2.5}$ by one-half (from 0.32 to 0.16) and the durability of the mitigation with the ratio of indoor to ambient $PM_{2.5}$ remaining quite low (indoor home and cooking periods, mean $PM_{2.5}$ of 8.3 $\mu g/m^3$) even when ambient $PM_{2.5}$ was quite high at 101 to 200 $\mu g/m^3$.

A second limitation is the generalizability of results to the US diplomatic corps. The $PM_{2.5}$ personal monitoring studies were conducted in just one highly polluted city, Kathmandu, and the findings may not be generalizable to other diplomats' exposure in other highly polluted cities, based on differences in $PM_{2.5}$ sources, weather trends, local crime and safety levels, diplomats' housing quality and daily patterns including time spent indoors and in other microenvironments. Ideally,$PM_{2.5}$ personal monitoring studies would have been conducted in other cities, including cities with high ambient $PM_{2.5}$ such as New Delhi, Dhaka, or Lahore, as well as in cities with moderately high $PM_{2.5}$, and cities with low

$PM_{2.5}$ levels, including Washington, D.C. Inferences about diplomats' personal exposure and time in microenvironments for my thesis were primarily based on observations on data collected in Kathmandu. It is possible that diplomats $PM_{2.5}$ personal exposure may be higher in cities with ambient $PM_{2.5}$ levels that are lower than that reported in Kathmandu, due to a variety of factors including ambient temperature, local safety, availability of outdoor activities, housing quality and mitigation used at home. The results of the health modeling study are not intended to be generalizable to all US diplomats since the study was conducted among using a finite set of 20-year diplomatic career assignments and among just three age groups. The $PM_{2.5}$-related impacts on each diplomat's mortality will be a function of a variety of factors including the cities where the diplomat lives during their career; the ambient $PM_{2.5}$ in those cities at the time of the diplomatic assignments; the age of the diplomat at the time of each assignment; the number of years spent in each location, the amount of air purifier usage in the diplomat's residence; the amount of time the diplomat spends outdoors, the diplomats' usage of other $PM_{2.5}$ mitigation efforts including improving the airtightness of the home, use of a respirator or other mask while outdoors, and mitigation efforts used while commuting by car; and the timing, type and intensity of exercise conducted while outdoors.

A third limitation of my thesis is that the research does not include any directly measured, or observed, health data. The modelling study made estimations of the mortality impact of $PM_{2.5}$ exposure for US diplomats and reflected their frequent relocations, however, the model was not informed by mortality rates directly observed for the diplomatic corps. Mortality is not currently systematically tracked for retired diplomats. The sensitivity analysis in health modeling study explored the validity of the models' findings, including restricting the US mortality data in the model to that of US citizens with a similar SES, based on household income, and this modification had a minimal impact on the life expectancy calculations. The sensitivity analysis also included explorations of the upper and lower limits of the concentration response functions and the lags in exposure and health outcomes. Ultimately, modifying the lags had the greatest impact on the life expectancy estimates and suggest the opportunity for further exploration of lags. Also of note, the published papers included in Chapters 4 and 5 did not include a health component and while the personal monitoring studies included collection of a single blood pressure, heart rate, respiratory rate, pulse oximetry and peak flow measurement at the conclusion of each 48-hour monitoring session, it was later deemed that the data was not granular enough to draw any meaningful associations between the health measurements and antecedent $PM_{2.5}$ exposure.

An additional limitation of the research is the question as to whether the results may be applicable to other populations such as military corps, international students, or other migrants including refugees and asylees. US diplomats differ in several ways from the aforementioned populations including their access to high quality housing, food, and medical care. In concert with the high quality housing, in many international postings, US diplomats are provided with air purifiers free of charge. US diplomats often work in buildings with highly filtered air. The US diplomatic population also has a higher SES than the general US population and results from studies of US diplomats may not be generalizable to the general population of the US or other highly industrialized countries (Glassdoor, 2023; United States Census Bureau, 2022). While some of the broad findings from the research may be meaningful for other populations that have relocated, such as the implications of moving from a high $PM_{2.5}$ to a low $PM_{2.5}$ location and the possible related benefit for lung function among children, it is expected that the model used to estimate mortality for diplomats would have to be tailored to individual populations in order to optimize accuracy.

An additional limitation of my thesis research is that the health model did not include a measure of risk related to the location specific $PM_{2.5}$ sources in each of the cities included in the ten illustrative assignment scenarios. The GBD 2019 C-R functions were based on extensive reviews of published studies of $PM_{2.5}$ levels and mortality from numerous global locations, however, the C-R functions were applied according to ambient $PM_{2.5}$ irrespective of the geographical location and $PM_{2.5}$ composition. While the GBD includes findings from research conducted in many countries, much of the GBD's evidence is based on research conducted in the US and Canada and, as such, the GBD's reported C-R functions may be more heavily based on the health effects associated with $PM_{2.5}$ sources in the US and Canada. $PM_{2.5}$ source attribution information should be considered for further model development as the $PM_{2.5}$ composition has a direct bearing on the $PM_{2.5}$ related health effects, with $PM_{2.5}$ due to open fires and road transportation suspected to have greater toxicity than other sources of $PM_{2.5}$ (Aguilera et al., 2021; Park et al., 2018).

The final limitation of my thesis is that it is difficult to validate the findings described in the modelling study (Chapter 6). The exploratory model relied heavily on the GBD C-R functions which have been closely studied and are well informed, however, it is based on US mortality rates which may be over-representing mortality among this population with high access to medical care and a relatively high SES. The inception and cessation lags are instrumental in the model, but there is limited published evidence on the duration and intensity of these lags.

7.5 Reflections on the research approach

During the course of the PhD research, which I began in April 2016, I developed many skills while undertaking the review and analytical components. In this section, I will reflect on each of the chapters, focusing on what I learned and the challenges I faced.

In the development of the systematic review protocol, I acquired knowledge on the method required to perform a comprehensive and robust systematic review. The experience of determining search terms and medical subject headings helped me gain an appreciation for how important the input is in framing the content of the review. Completing the search helped me have a working understanding of the different scientific databases including Medline, Global Health and Embase and the strengths and limitations of each. The process of using the Navigation Guide for the assessment of study bias, quality and strength helped reinforce my understanding of the methods to use in epidemiological studies. Reviewing more than 300 abstracts, determining which papers met the review's inclusion criteria and ultimately summarizing the key findings from the papers reviewed for the study was a large undertaking and was very rewarding when the analysis and manuscript were complete. In future reviews, I would spend additional time adding more specific language to the inclusion and exclusion criteria for the review as we had difficulty, in some cases, deciding which papers to include or exclude from the review. I would also like to develop a machine learning program to screen papers and to extract data in order to optimize efficiency. I now feel much more knowledgeable and skilled at completing a systematic review than I did prior to beginning the PhD program.

There are several aspects of the personal monitoring studies described in Chapters 4 and 5 that I would do differently if given the chance. The first would be to complete a full year of personal monitoring among the 30 diplomats selected for the study. This would allow for seasonal comparisons of personal exposure, and it is anticipated that personal exposure would be much lower than levels reported in Chapters 4 and 5 as that data was collected during fall and winter, when $PM_{2.5}$ is at its highest.

Unfortunately, the original research plan for the study described in Chapter 4 was halted in March 2020 due to the lockdown measures implemented in Kathmandu by the Nepalese government. At this time, more than half of the study participants departed Nepal and relocated to the US. Another element of the personal monitoring study that I would change is to ask study participants to record the exact timing of cooking at home in their daily log. Unfortunately, we did not ask study participants to make a note of this and the cooking periods were later determined post-hoc based an examination of personal monitoring data in conjunction with a review of the temperature recorded by the personal monitor. I would also implement global positioning system (GPS) monitoring among study participants. The personal exposure monitor used in the study was supposed to record GPS coordinates, however, there were delays in GPS data recording due to difficulty with the monitors' communication with the Kathmandu cellular phone network and the problem was only rectified halfway through the study. A solution to this issue could have been to ask study participants to wear a watch that recorded GPS coordinates and to later link the GPS data with the personal monitoring and ambient data. GPS data would allow for increased precision in determining locations outside of the home and I relied primarily on participants' time activity diaries for this information in the study.

7.6 Areas for future research

Several ideas for further research have been generated during the research activities conducted as part of my thesis. The future research ideas proposed below would help fill gaps in evidence identified in the published papers in Chapters 3-5 and in the submitted manuscript in Chapter 6.

7.6.1 Cohort study of diplomats

While the results of my literature review in Chapter 3 identified changes in lung function, respiratory symptoms and respiratory hospitalizations in children aged 2-5 years and increased mortality, additional studies are needed to further identify and characterize changes in $PM_{2.5}$ related health outcomes among US diplomats and accompanying family members. The ideal strategy to better understand the health effects of air pollution on US diplomats would be to establish a prospective cohort study of the US diplomatic corps and their accompanying family members, including children. The cohort study would include a detailed medical assessment and exposure questionnaire at baseline, with annual assessments to identify health outcomes previously linked to air pollution exposure including IHD, stroke, COPD, LRI, type 2 diabetes and lung cancer morbidity and mortality (GBD Risk Factors Collaborators, 2020b) and conditions reported in my literature review paper including changes in lung function (Avol et al., 2001; Kinney & Lippmann, 2000), peak flow (Renzetti et al., 2009; Wu et al., 2014), heart rate and HRV (Vilcassim et al., 2019), blood pressure (Wu et al., 2013), birth outcomes including SGA and LBW (Pereira et al., 2016) and PTB (L. Liang et al., 2019). Most US Embassies have a medical unit located in the Embassy and elements of the cohort study could be incorporated into diplomats' medical examinations which are required before relocation to a new Embassy assignment.

As prospective cohort studies are very expensive and take many years to come to fruition (likely more than 20 years), a more practical and timely recommendation is to conduct a retrospective cohort study that includes precise timing and location of each international relocation, with ambient $PM_{2.5}$ levels, either based on ground level data or modeled ambient data, such as that from Shaddick *et al*. for locations and time periods when ground level $PM_{2.5}$ data was not available (Shaddick et al., 2018; World Health Organization, 2022). Health outcome data, including medical diagnoses using ICD-10 coding, could be collected from the US Department of State's electronic medical records system, and could be supplemented with ICD-10 billing codes obtained from diplomats' medical insurance providers. Diplomats and their accompanying family members would need to be contacted in order to collect information about mortality, as information on deaths among the diplomatic corps is not currently collected after the diplomat has retired.

7.6.2 Additional personal exposure studies

A second recommendation seeks to build upon the results discussed in Chapters 4 and 5 regarding microenvironments linked to air pollution exposure and the effectiveness of air purifiers and improved home air tightness in diplomats' residences. Additional research is needed to understand how effective the mitigation strategies examined in Chapter 5 may be in other highly polluted cities where housing construction and time spent in various microenvironments may be different than in Kathmandu. Personal exposure is expected to vary in different cities around the world due to differences in the time spent in at home, outdoors and in other microenvironments due to a variety of factors including the weather, availability of commercial and other social activities in the city, and the security level in the city. Personal exposure will also be impacted by the local housing quality, availability of air purifiers, and diplomats' willingness and ability to use air purifiers in various cities hosting a US Embassy. While the intervention study conducted among US diplomats and adult family members in Kathmandu indicated that personal exposure to $PM_{2.5}$ was approximately one-third of the ambient $PM_{2.5}$,with that figure halved when a high level of mitigation was used in diplomatic residences, it is unknown whether these figures apply to diplomats and family members in other global cities. It is also unknown how personal exposure may vary in areas with varying $PM_{2.5}$ sources including black carbon, primary organic aerosols (POA) and anthropogenic secondary organic aerosols (aSOA) (Chowdhury et al., 2022).

7.6.3 Conduct additional research on lags on $PM_{2.5}$ exposure and health outcomes

As evidenced by the work described in Chapter 6 of my thesis, little is known about cessation lags following reductions in air pollution exposure and even less is known about inception lags. Both lags were key components of my model to estimate mortality impacts across the lifespan associated with diplomatic assignments. A final recommendation to help inform understanding about the health effects of air pollution exposure on US diplomats is to conduct population level empirical studies to better understand the relationship between $PM_{2.5}$ exposure and mortality due to IHD, stroke, COPD, LRI, type 2 diabetes and lung cancer following an increase (inception lag) and decrease (cessation lag) in ambient $PM_{2.5}$. Lags were a crucial element of the health impact model I created as evidenced in the sensitivity analysis of the paper with a notable increase in DLL when inception lags were removed and a reduction in DLL when cessation lags were removed. Increased understanding about the precise timing and shape of inception and cessation lags for each of the conditions examined in the model will help increase the accuracy of the life expectancy estimates for US diplomats.

7.7 Policy implications of the thesis

The first policy implication of my research relates to the findings presented in Chapter 4 which highlighted the burden of personal exposure to $PM_{2.5}$ linked to cooking at home. US government policy makers may want to consider improving the cooking ventilation systems used in diplomats' residences and to consider opening windows when ambient $PM_{2.5}$ levels are low (less than or equal to 5 $\mu g/m^3$) to enhance the removal of $PM_{2.5}$ generated while cooking from the home (Kang et al., 2019; Xiang, Hao, et al., 2021). Research conducted by Kang *et al*. in Seoul, South Korea found that the PM concentration was effectively decreased when both natural ventilation and the range hood system were used simultaneously. Xiang *et al*. reported that use of a range hood system, increased ventilation achieved through opening kitchen windows, and the use of an air purifier in the kitchen resulted in 60 to 70% reduction in $PM_{2.5}$ compared to cooking scenarios with no interventions used.

A second policy implication is related to the results in Chapters 4 and 5 which highlighted the importance of ensuring a high level of air filtration in diplomats' residences. These findings support the recommendation to ensure that air purifiers are available for US diplomats to use in their residences in all cities with ambient mean annual $PM_{2.5}$ that is higher than the US national mean annual $PM_{2.5}$ level.

However, it is worth emphasizing again that high-capacity air purifiers are expensive, and the cost is likely a barrier for many settings, including public facilities where vulnerable populations spend time. Unfortunately, most local citizens people living in highly polluted cities do not have access to as many air purifiers as the participants in the Kathmandu studies. Research conducted among citizens of the People's Republic of China reported that local citizens were willing to pay approximately 5 US dollars per 1 $\mu g/m^3$ of PM_{10} removed from their home through the use of air purifiers, although findings varied by location and ambient PM_{10} levels (Ito & Zhang, 2016). Air purifiers are expensive, as is the cost of electricity to operate air purifiers, and the recommendations highlighted in Chapter 5 make this mitigation option impractical for persons with limited financial resources. High electricity usage has negative effects on the environment including carbon dioxide emissions (Saint Akadiri et al., 2020; Yildiz et al., 2019), high use of water resources to produce steam and cooling at electric power plants (Ehyaei et al., 2021), and in times of power outages, when diesel fuel powered generators are used, $PM_{2.5}$, nitrogen oxides, carbon monoxide and other pollutants are produced (Liang et al., 2005; Lopatin, 2020). Use of air purifiers is a mitigation option that is not a viable recommendation for many populations, but it is the primary mitigation strategy used by the US government to help limit air pollution exposure for US diplomats working in highly polluted cities, with the hope that diplomats' air quality level in their diplomatic residences abroad is similar to levels reported in the US (United States Department of State, 2022a). Air purifiers for use in homes are not provided to locally employed staff members who work in US Embassies in highly polluted cities, and this policy does have indicates a health equity concern because Americans diplomats are provided a resource that host country nationals working in the Embassy are not provided (Wong, 2013b). Locally employed US Embassy staff have the benefit of working in highly filtered air while working in the Embassy, with indoor $PM_{2.5}$ levels at or near zero $\mu g/m^3$ for 40 hours per week. Locally employed US Embassy staff and other host country nationals have access to ambient $PM_{2.5}$ data collected by US Embassies in many highly polluted cities. US Embassy messaging about $PM_{2.5}$ data has led to reductions in local $PM_{2.5}$ levels and reductions in $PM_{2.5}$ related premature mortality in these cities (Jha & Nauze, 2022). This topic merits further reflection to identify opportunities to increase global health equity among US diplomats and locally employed staff who work at US Embassies in highly polluted cities.

A third policy implication of my research is that diplomats, as well as locally employed staff at US Embassies and Consulates, may benefit from efforts to study local diurnal $PM_{2.5}$ trends and share this information with the public, including diplomats, so that they can make informed decisions about when they spend time outdoors. Time spent outdoors was the one of the largest contributors to personal exposure to $PM_{2.5}$ in the results presented in Chapter 4. Prior survey research conducted in the US suggested that less than 20% of survey respondents indicated using publicly available air quality data to help determine when they spent time outdoors, with higher use of the data to drive decision make was reported among persons with asthma compared to those who did not have asthma (Laumbach et al., 2015; Wen et al., 2009). It is expected that US diplomats may have a higher rate of using air quality data to drive their activities as US diplomats included in the studies in Chapters 4 and 5 anecdotally indicated that they were more focused on making decisions about timing outdoor activities based on the US Embassy's $PM_{2.5}$ data than they had been while working in previous diplomatic postings where $PM_{2.5}$ was not measured or reported by the US Embassy.

A fourth policy implication is based on the reduction of indoor $PM_{2.5}$ following the addition of high-capacity air purifiers reported in Chapter 5 and includes the option to increase the use of air purifiers in public buildings in highly polluted cities. Wide scale use of air purifiers in public buildings such as hospitals and schools in highly polluted cities has the potential to considerably reduce $PM_{2.5}$ exposure for the general public and, in particular, for vulnerable populations (Bragoszewska & Biedron, 2021;

Zhou et al., 2022). However, there are barriers to broadened use of air purifiers including limited financial and infrastructure resources particularly in low to middle income countries. While the findings reported in Chapter 5 are encouraging, it may not be practical to implement the $PM_{2.5}$ reduction strategy described in this research in locations that have limited funding to support these efforts.

An additional policy implication is to consider using low-cost efforts to reduce indoor $PM_{2.5}$ such as adding caulk or weatherproofing tape to windows and unused exterior doors, particularly when costs are a barrier to purchasing air purifiers (Yang et al., 2022; Yu et al., 2020). Concern should be taken in homes where cooking occurs over an open flame, or a wood or coal stove is used to heat the home (Militello-Hourigan & Miller, 2018; Shrubsole et al., 2016; Yip et al., 2017; Zhu & Wang, 2003). In these homes it may not be appropriate to improve the home tightness.

A final policy implication is based on the modeling study included in Chapter 6 which suggested that, where possible, US government agencies and diplomats may want to consider scheduling work in cities with high $PM_{2.5}$ at the beginning of the career rather than at older ages, when baseline mortality rates increase steeply. And a final policy implication is based on the modeling study results which suggested that after completion of an assignment in a city with high $PM_{2.5}$, US diplomats may also want to request that their next assignment be in a city with low $PM_{2.5}$, if possible. It should be noted that there are many important factors in determining staffing assignments including the suitability for available positions, amount of training and expertise needed in various positions, as well as other personal and family health and safety considerations (United States Department of State, 2020, 2022a). Although ambient $PM_{2.5}$ could impact diplomats' health, it is only one of many important factors that employers may want to consider when determining global staffing assignments and the duration of assignments.

The US diplomatic corps is a population that is underrepresented in the literature, with very limited publications on health outcomes among diplomats and no prior publications on $PM_{2.5}$ related health impacts among US diplomats. Relocation studies could be developed and conducted among US diplomats to examine the change in health outcomes identified in the literature review (Chapter 3) including lung function, cardiovascular and respiratory symptoms. The findings of my PhD thesis support the use of air purifiers in diplomats' homes in highly polluted cities, in order to reduce $PM_{2.5}$ exposure and related impacts on mortality. The health model developed is quite novel with the incorporation of GBD C-R functions, US mortality statistics and lags in exposure and health effects, with mortality for diplomats compared to that of Americans living in the United States in order to identify the decrease in life expectancy due to $PM_{2.5}$ exposure during diplomats' 20-year career with the US government. The model could be further refined to include actual human resources data on staffing patterns for US diplomats in order to create an overall mean estimate of the impact of $PM_{2.5}$ exposure on mortality for diplomats.

7.8 Concluding statements

My PhD research examined the health effects of $PM_{2.5}$ exposure on US diplomats and their accompanying family members, who have frequent relocations and changes in ambient $PM_{2.5}$ exposure levels throughout their life. Prior to completing this research, very few studies were conducted among persons with relocations to areas with a change in ambient $PM_{2.5}$ and there were no published studies of personal exposure to $PM_{2.5}$ among the US diplomatic corps. The results of my PhD indicated that additional monitoring of health outcomes identified in the literature review, including reduced lung function in locations with high $PM_{2.5}$, may be helpful in guiding decision making for diplomats and their family members. Time spent outdoors and cooking were amongst the largest contributors to personal exposure to $PM_{2.5}$ for diplomats in one highly polluted city and added mitigation in diplomatic residences in cities with high $PM_{2.5}$ can help drastically reduce $PM_{2.5}$ exposure to levels comparable to the ambient $PM_{2.5}$ in the United States. The modelling results suggests that life expectancy would decrease for diplomats and accompanying family members who spend numerous years living in locations with high $PM_{2.5}$ with increased effects were found as age at the time of the assignment increased. This research also indicates that alternating assignments in high and low $PM_{2.5}$ cities may reduce the $PM_{2.5}$ related mortality associated with time spent in high $PM_{2.5}$ cities. Diplomats have the opportunity to reduce the impact on their health and life expectancy by using air purifiers and improving the home air tightness in their residence during assignments in high $PM_{2.5}$ cities. Diplomats can also reduce their $PM_{2.5}$ exposure and related health impacts by learning more about diurnal $PM_{2.5}$ patterns in the city where they are working and spending time outdoors at times when the ambient $PM_{2.5}$ is low. Results from this PhD thesis offer insights into the health effects of $PM_{2.5}$ exposure for US diplomats as well as strategies for diplomats to reduce their $PM_{2.5}$ exposure and related health impacts during their diplomatic service. These findings and insights may also be helpful for other populations who live and work in highly polluted cities, and to government officials to provide evidence as to the importance of ensuring that all citizens, regardless of their SES, have access to strategies and resources to ensure a low $PM_{2.5}$ level in their home, in accordance with the WHO air quality standards.

Bibliography

Aguilera, R., Corringham, T., Gershunov, A., & Benmarhnia, T. (2021). Wildfire smoke impacts respiratory health more than fine particles from other sources: observational evidence from Southern California. *Nature communications*, *12*(1), 1493. https://doi.org/10.1038/s41467-021-21708-0

Anonymous. (2020, April 12, 2020). It's the Brick Kilns. *The Kathmandu Post*. https://kathmandupost.com/editorial/2020/04/12/it-s-the-brick-kilns

Applied Particle Technology. (2020). *Automated Environmental Health and Safety*. https://appliedparticletechnology.com/

Apte, J. S., Brauer, M., Cohen, A., Ezzati, M., & Pope, C. A. (2018). Ambient PM2.5 Reduces Global and Regional Life Expectancy. *Environmental Science & Technology Letters*, *S*, S46-51.

Avol, E. L., Gauderman, W. J., Tan, S. M., London, S. J., & Peters, J. M. (2001). Respiratory effects of relocating to areas of differing air pollution levels. *American Journal of Respiratory & Critical Care Medicine*, *164*(11), 2067-2072. https://doi.org/10.1164/ajrccm.164.11.2102005

Awad, Y. A., Di, Q., Wang, Y., Choirat, C., Coull, B. A., Zanobetti, A., & Schwartz, J. (2019). Change in PM2.5 exposure and mortality among Medicare recipients: Combining a semi-randomized approach and inverse probability weights in a low exposure population. *Environmental Epidemiology*, *3*(4), e054. https://doi.org/10.1097/EE9.0000000000000054

Barkjohn, K. K., Bergin, M. H., Norris, C., Schauer, J. J., Zhang, Y., Black, M., Hu, M., & Zhang, J. (2020). Using Low-cost sensors to Quantify the Effects of Air Filtration on Indoor and Personal Exposure Relevant PM2.5 Concentrations in Beijing, China. *Aerosol and Air Quality Research*, *20*(2), 297-313. https://doi.org/10.4209/aaqr.2018.11.0394

Barkjohn, K. K., Norris, C., Cui, X., Fang, L., Zheng, T., Schauer, J. J., Li, Z., Zhang, Y., Black, M., Zhang, J. J., & Bergin, M. H. (2021). Real-time measurements of PM2.5 and ozone to assess the effectiveness of residential indoor air filtration in Shanghai homes. *Indoor Air*, *31*(1), 74-87. https://doi.org/10.1111/ina.12716

Basnet, B. B., Bishwakarma, K., Pant, R. R., Dhakal, S., Pandey, N., Gautam, D., Ghimire, A., & Basnet, T. B. (2021). Combating the COVID-19 pandemic: experiences of the first wave from Nepal. *Frontiers in Public Health*, *9*, 613402.

Beelen, R., Raaschou-Nielsen, O., Stafoggia, M., Andersen, Z. J., Weinmayr, G., Hoffmann, B., Wolf, K., Samoli, E., Fischer, P., Nieuwenhuijsen, M., Vineis, P., Xun, W. W., Katsouyanni, K., Dimakopoulou, K., Oudin, A., Forsberg, B., Modig, L., Havulinna, A. S., Lanki, T., . . . Hoek, G. (2014). Effects of long-term exposure to air pollution on natural-cause mortality: an analysis of 22 European cohorts within the multicentre ESCAPE project. *Lancet*, *383*(9919), 785-795. https://doi.org/10.1016/S0140-6736(13)62158-3

Ben-Shlomo, Y., Smith, G. D., Shipley, M. J., & Marmot, M. G. (1994). What determines mortality risk in male former cigarette smokers? *American Journal of Public Health*, *84*(8), 1235-1242. https://doi.org/10.2105/ajph.84.8.1235

Bennett, D. H., Moran, R. E., Krakowiak, P., Tancredi, D. J., Kenyon, N. J., Williams, J., & Fisk, W. J. (2022). Reductions in particulate matter concentrations resulting from air filtration: A randomized sham-controlled crossover study. *Indoor Air*, *32*(2), e12982. https://doi.org/10.1111/ina.12982

Berman, J. D., & Ebisu, K. (2020). Changes in U.S. air pollution during the COVID-19 pandemic. *Science of the Total Environment*, *739*, 139864. https://doi.org/10.1016/j.scitotenv.2020.139864

Blueair. (2022a). *Classic 203 Slim*. https://www.blueair.com/us/refurbished-air-purifiers/classic-203-slim/1422.html

Blueair. (2022b). *Classic 605*. https://www.blueair.com/us/air-purifiers/classic-605/1641.html

Boomhower, S. R., Long, C. M., Li, W., Manidis, T. D., Bhatia, A., & Goodman, J. E. (2022). A review and analysis of personal and ambient PM(2.5) measurements: Implications for epidemiology studies. *Environ Res*, *204*(Pt B), 112019. https://doi.org/10.1016/j.envres.2021.112019

Bragoszewska, E., & Biedron, I. (2021). Efficiency of Air Purifiers at Removing Air Pollutants in Educational Facilities: A Preliminary Study. *Frontiers in Enviornmental Science*, *9*. https://doi.org/https://doi.org/10.3389/fenvs.2021.709718

Brauner, E. V., Forchhammer, L., Moller, P., Barregard, L., Gunnarsen, L., Afshari, A., Wahlin, P., Glasius, M., Dragsted, L. O., Basu, S., Raaschou-Nielsen, O., & Loft, S. (2008). Indoor particles affect vascular function in the aged: an air filtration-based intervention study. *American Journal of Respiratory & Critical Care Medicine*, *177*(4), 419-425. https://doi.org/10.1164/rccm.200704-632OC

Brehmer, C., Norris, C., Barkjohn, K. K., Bergin, M. H., Zhang, J., Cui, X., Teng, Y., Zhang, Y., Black, M., Li, Z., Shafer, M. M., & Schauer, J. J. (2020). The impact of household air cleaners on the oxidative potential of PM(2.5) and the role of metals and sources associated with indoor and outdoor exposure. *Environ Res*, *181*, 108919. https://doi.org/10.1016/j.envres.2019.108919

Brunekreef, B., Beelen, R., Hoek, G., Schouten, L., Bausch-Goldbohm, S., Fischer, P., Armstrong, B., Hughes, E., Jerrett, M., & van den Brandt, P. (2009). Effects of long-term exposure to traffic-related air pollution on respiratory and cardiovascular mortality in the Netherlands: the NLCS-AIR study. *Research Report - Health Effects Institute*(139), 5-71; discussion 73-89.

Bruno, D. (2013). Living in Beijing's Polluted Air. https://www.washingtonpost.com/national/health-science/living-in-beijings-polluted-air/2013/03/11/6606e45e-7489-11e2-8f84-3e4b513b1a13_story.html

Burnett, R. T., Pope, C. A., 3rd, Ezzati, M., Olives, C., Lim, S. S., Mehta, S., Shin, H. H., Singh, G., Hubbell, B., Brauer, M., Anderson, H. R., Smith, K. R., Balmes, J. R., Bruce, N. G., Kan, H., Laden, F., Pruss-Ustun, A., Turner, M. C., Gapstur, S. M., . . . Cohen, A. (2014). An integrated risk function for estimating the global burden of disease attributable to ambient fine particulate matter exposure. *Environmental Health Perspectives*, *122*(4), 397-403. https://doi.org/10.1289/ehp.1307049

Burns, J., Boogaard, H., Polus, S., Pfadenhauer, L. M., Rohwer, A. C., van Erp, A. M., Turley, R., & Rehfuess, E. A. (2020). Interventions to reduce ambient air pollution and their effects on health: An abridged Cochrane systematic review. *Environment International*, *135*, 105400. https://doi.org/10.1016/j.envint.2019.105400

Castelli, F. (2018). Drivers of migration: why do people move? *Journal of Travel Medicine*, *25*(1). https://doi.org/10.1093/jtm/tay040

Centers for Disease Control and Prevention. (2021). *National Vital Statistics System, Mortality 1999-2020 on CDC WONDER Online Database* https://doi.org/http://wonder.cdc.gov/ucd-icd10.html

Chen, H., Kaufman, J. S., Olaniyan, T., Pinault, L., Tjepkema, M., Chen, L., van Donkelaar, A., Martin, R. V., Hystad, P., Chen, C., Kirby-McGregor, M., Bai, L., Burnett, R. T., & Benmarhnia, T. (2021). Changes in exposure to ambient fine particulate matter after relocating and long term survival in Canada: quasi-experimental study. *BMJ*, *375*, n2368. https://doi.org/10.1136/bmj.n2368

Chen, J., & Hoek, G. (2020). Long-term exposure to PM and all-cause and cause-specific mortality: A systematic review and meta-analysis. *Environment International*, *143*, 105974. https://doi.org/10.1016/j.envint.2020.105974

Chen, K., Wang, M., Huang, C., Kinney, P. L., & Anastas, P. T. (2020). Air pollution reduction and mortality benefit during the COVID-19 outbreak in China. *The lancet. Planetary Health*, *4*(6), e210-e212. https://doi.org/10.1016/S2542-5196(20)30107-8

Chen, R., Kan, H., Chen, B., Huang, W., Bai, Z., Song, G., & Pan, G. (2012). Association of particulate air pollution with daily mortality: the China Air Pollution and Health Effects Study. *American journal of epidemiology*, *175*(11), 1173-1181.

Chen, R., Zhao, A., Chen, H., Zhao, Z., Cai, J., Wang, C., Yang, C., Li, H., Xu, X., Ha, S., Li, T., & Kan, H. (2015). Cardiopulmonary benefits of reducing indoor particles of outdoor origin: a randomized, double-blind crossover trial of air purifiers. *Journal of the American College of Cardiology*, *65*(21), 2279-2287. https://doi.org/https://dx.doi.org/10.1016/j.jacc.2015.03.553

Chowdhury, S., Pozzer, A., Haines, A., Klingmuller, K., Munzel, T., Paasonen, P., Sharma, A., Venkataraman, C., & Lelieveld, J. (2022). Global health burden of ambient PM(2.5) and the contribution of anthropogenic black carbon and organic aerosols. *Environment International*, *159*, 107020. https://doi.org/10.1016/j.envint.2021.107020

Christidis, T., Erickson, A. C., Pappin, A. J., Crouse, D. L., Pinault, L. L., Weichenthal, S. A., Brook, J. R., van Donkelaar, A., Hystad, P., Martin, R. V., Tjepkema, M., Burnett, R. T., & Brauer, M. (2019). Low concentrations of fine particle air pollution and mortality in the Canadian Community Health Survey cohort. *Environmental Health: A Global Access Science Source*, *18*(1), 84. https://doi.org/10.1186/s12940-019-0518-y

Clancy, L., Goodman, P., Sinclair, H., & Dockery, D. W. (2002). Effect of air-pollution control on death rates in Dublin, Ireland: an intervention study. *Lancet*, *360*(9341), 1210-1214. https://doi.org/10.1016/S0140-6736(02)11281-5

Cohen, A. J., Brauer, M., Burnett, R., Anderson, H. R., Frostad, J., Estep, K., Balakrishnan, K., Brunekreef, B., Dandona, L., Dandona, R., Feigin, V., Freedman, G., Hubbell, B., Jobling, A., Kan, H., Knibbs, L., Liu, Y., Martin, R., Morawska, L., . . . Forouzanfar, M. H. (2017). Estimates and 25-year trends of the global burden of disease attributable to ambient air pollution: an analysis of data from the Global Burden of Diseases Study 2015. *Lancet*, *389*(10082), 1907-1918. https://doi.org/10.1016/S0140-6736(17)30505-6

Cohen, A. J., Ross Anderson, H., Ostro, B., Pandey, K. D., Krzyzanowski, M., Kunzli, N., Gutschmidt, K., Pope, A., Romieu, I., Samet, J. M., & Smith, K. (2005). The global burden of disease due to outdoor air pollution. *Journal of Toxicology & Environmental Health Part A*, *68*(13-14), 1301-1307. https://doi.org/10.1080/15287390590936166

Committee on the Medical Effects of Air Pollutants. (2010). *The Mortality Effects of Long-Term Exposure to Particulate Air Pollution in the United Kingdom*. Retrieved from https://www.gov.uk/government/publications/comeap-mortality-effects-of-long-term-exposure-to-particulate-air-pollution-in-the-uk

Committee on the Medical Effects of Air Pollutants. (2018). *Statement on quantifying mortality associated with long-term average concentrations of fine particulate matter (PM2.5)*. Retrieved from https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/734813/COMEAP_PM_2.5_statement.pdf

Committee on the Medical Effects of Air Pollutants. (2022). *Statement on quantifying mortality associated with long-term exposure to PM2.5*. Retrieved from https://assets.publishing.service.gov.uk/media/623302158fa8f504aa780865/COMEAP_Statement_on_PM2.5_mortality_quantification.pdf

Cooper, E., Milner, J., Wang, Y., Stamp, S., & Mumovic, D. (2022). Modelling the impact on mortality of using portable air purifiers in UK homes. *Atmospheric Environment*, *289*. https://doi.org/https://doi.org/10.1016/j.atmosenv.2022.119311

Cox, J., Isiugo, K., Ryan, P., Grinshpun, S. A., Yermakov, M., Desmond, C., Jandarov, R., Vesper, S., Ross, J., Chillrud, S., Dannemiller, K., & Reponen, T. (2018). Effectiveness of a portable air cleaner in removing aerosol particles in homes close to highways. *Indoor Air*, *28*(6), 818-827. https://doi.org/10.1111/ina.12502

Cromar, K. R., Gladson, L. A., Hicks, E. A., Marsh, B., & Ewart, G. (2021). Excess Morbidity and Mortality Associated with Air Pollution above American Thoracic Society Recommended Standards, 2017-2019. *Annals of the American Thoracic Society*. https://doi.org/10.1513/AnnalsATS.202107-860OC

Cummings, C. P., J.; Lauro, D.; Foresti, M.,. (2015). *Why people move: understanding the drivers and trends of migration to Europe*. Retrieved from https://www.odi.org/publications/10217-why-people-move-understanding-drivers-and-trends-migration-europe

Deng, G. L., Z.; Wang, Z.; Gao, J.; Xu, Z.; Li, J.; Wang, Z. (2017). Indoor/outdoor relationship of PM2.5 concentration in typical buildings with and without air cleaning in Beijing. *Indoor and Built Environment*, *26*, 60-68. https://doi.org/10.1177/1420326X15604349

Edwards, L., Wilkinson, P., Rutter, G., Iverson, L., & Milojevic, A. (2023). Impact of mitigation measures to improve home indoor air quality in Kathmandu, Nepal. *Environmental Research: Health*, *1*. https://doi.org/https://doi.org/10.1088/2752-5309/acb663

Edwards, L., Wilkinson, P., Rutter, G., & Milojevic, A. (2022). Health effects in people relocating between environments of differing ambient air pollution concentrations: A literature review. *Environmental Pollution*, *292*(Pt A), 118314. https://doi.org/10.1016/j.envpol.2021.118314

Edwards L. (2019). *The PM2.5 Exposure and Associated Health Effects on US Government Employees and Family Members Living Overseas (Upgrade Report)* London School of Hygiene and Tropical Medicine].

Edwards L., & Beres, J. (2017). *PM2.5 Personal Exposure Monitoring Study in Kampala, Uganda (Unpublished results, internal US government materials).*

Edwards L., Beres, J., & Huson, C. (2018). *PM2.5 Personal Monitoring Study in Riyadh, Saudi Arabia (Unpublished research, internal US government materials).*

Ehyaei, M. A., Baloochzadeh, S., & Ahmadi, A. (2021). Energy, exergy, economic, exergoenvironmental, and environmental analyses of a multigeneration system to produce electricity, cooling, potable water, hydrogen and sodium-hypochlorite. *Desalination*, *501*.

Eli, A. L., J. Baral, P. Saikawa, E. (2020). *Dirty Stacks, High Stakes: An Overview of the Brick Sector in South Asia*. http://documents1.worldbank.org/curated/en/685751588227715919/pdf/Dirty-Stacks-High-Stakes-An-Overview-of-Brick-Sector-in-South-Asia.pdf

Evangelopoulos, D., Katsouyanni, K., Keogh, R. H., Samoli, E., Schwartz, J., Barratt, B., Zhang, H., & Walton, H. (2020). PM2.5 and NO2 exposure errors using proxy measures, including derived personal exposure from outdoor sources: A systematic review and meta-analysis. *Environment International*, *137*, 105500. https://doi.org/10.1016/j.envint.2020.105500

Fisk, W. J., & Chan, W. R. (2017). Effectiveness and cost of reducing particle-related mortality with particle filtration. *Indoor Air*, *27*(5), 909-920. https://doi.org/10.1111/ina.12371

Fuller, R., Landrigan, P. J., Balakrishnan, K., Bathan, G., Bose-O'Reilly, S., Brauer, M., Caravanos, J., Chiles, T., Cohen, A., Corra, L., Cropper, M., Ferraro, G., Hanna, J., Hanrahan, D., Hu, H., Hunter, D., Janata, G., Kupka, R., Lanphear, B., . . . Yan, C. (2022). Pollution and health: a progress update. *The lancet. Planetary Health*, *6*(6), e535-e547. https://doi.org/10.1016/S2542-5196(22)00090-0

Gan, W. Q., Tamburic, L., Davies, H. W., Demers, P. A., Koehoorn, M., & Brauer, M. (2010). Changes in residential proximity to road traffic and the risk of death from coronary heart disease [Research Support, Non-U.S. Gov't]. *Epidemiology*, *21*(5), 642-649. https://doi.org/https://dx.doi.org/10.1097/EDE.0b013e3181e89f19

GBD Risk Factors Collaborators. (2020a). *Ambient particulate matter pollution exposure summary statistics*. https://doi.org/https://ghdx.healthdata.org/gbd-2019

GBD Risk Factors Collaborators. (2020b). Global burden of 87 risk factors in 204 countries and territories, 1990-2019: a systematic analysis for the Global Burden of Disease Study 2019. *Lancet*, *396*(10258), 1223-1249. https://doi.org/10.1016/S0140-6736(20)30752-2

Giani, P., Castruccio, S., Anav, A., Howard, D., Hu, W., & Crippa, P. (2020). Short-term and long-term health impacts of air pollution reductions from COVID-19 lockdowns in China and Europe: a modelling study. *The lancet. Planetary Health*, *4*(10), e474-e482. https://doi.org/10.1016/S2542-5196(20)30224-2

Glassdoor. (2023). *Salary Details for a Foreign Service Officer at US Department of State*. Retrieved April 12, 2023 from https://www.glassdoor.com/Salary/U-S-Department-of-State-Foreign-Service-Officer-Salaries-E32768_D_KO24,47.htm

Guak, S., & Lee, K. (2018). Different relationships between personal exposure and ambient concentration by particle size. *Environmental Science & Pollution Research*, *25*(17), 16945-16950. https://doi.org/10.1007/s11356-018-1889-2

Guttikunda, S. K., & Goel, R. (2013). Health impacts of particulate pollution in a megacity—Delhi, India. *Environmental Development*, *6*, 8-20. https://doi.org/https://doi.org/10.1016/j.envdev.2012.12.002

Harris, G. (2015, May 29, 2015). Holding Your Breath in India. *New York Times*. https://www.nytimes.com/2015/05/31/opinion/sunday/holding-your-breath-in-india.html

Health Effects Institute. (2022). *Systematic Review and Meta-analysis of Selected Health Effects of Long-Term Exposure to Traffic-Related Air Pollution*. https://www.healtheffects.org/publication/systematic-review-and-meta-analysis-selected-health-effects-long-term-exposure-traffic

Health Effects Institute. (2023). State of Global Air 2023. www.stateofglobalair.org

Hopke, P. K., Dai, Q., Li, L., & Feng, Y. (2020). Global review of recent source apportionments for airborne particulate matter. *Science of the Total Environment*, *740*, 140091. https://doi.org/10.1016/j.scitotenv.2020.140091

Huangfu, P., & Atkinson, R. (2020). Long-term exposure to NO2 and O3 and all-cause and respiratory mortality: A systematic review and meta-analysis. *Environment International*, *144*, 105998. https://doi.org/10.1016/j.envint.2020.105998

Huson, C., Edwards, L., Beres, J., Sharma, R., Shahi, S., Sauran, S., & Quillin, W. (2017). *American Diplomats and Family Members Living in New Delhi, India: What Are the Impacts and Practical Mitigation for Air Pollution?* https://www.healtheffects.org/sites/default/files/ProgramBook-Abstracts042017.pdf

IQAir. (2022). *World's most polluted cities (historical data 2017-2022)* https://doi.org/https://www.iqair.com/world-most-polluted-cities

Ito, K., & Zhang, S. (2016). *Willingness to pay for clean air: evidence for air purifier markets in China*. https://www.nber.org/system/files/working_papers/w22367/w22367.pdf

Jha, A., & Nauze, A. (2022). US Embassy air-quality tweets led to global health benefits. *Proceedings of the National Academy of Sciences of the United States of America*, *119*(44), e2201092119. https://doi.org/10.1073/pnas.2201092119

Johnson, P. I., Koustas, E., Vesterinen, H. M., Sutton, P., Atchley, D. S., Kim, A. N., Campbell, M., Donald, J. M., Sen, S., Bero, L., Zeise, L., & Woodruff, T. J. (2016). Application of the Navigation Guide systematic review methodology to the evidence for developmental and reproductive toxicity of triclosan. *Environment International*, *92-93*, 716-728. https://doi.org/10.1016/j.envint.2016.03.009

Kajbafzadeh, M., Brauer, M., Karlen, B., Carlsten, C., van Eeden, S., & Allen, R. W. (2015). The impacts of traffic-related and woodsmoke particulate matter on measures of cardiovascular health: a HEPA filter intervention study. *Occupational & Environmental Medicine*, *72*(6), 394-400. https://doi.org/10.1136/oemed-2014-102696

Kang, K., Kim, H., Kim, D. D., Lee, Y. G., & Kim, T. (2019). Characteristics of cooking-generated PM(10) and PM(2.5) in residential buildings with different cooking and ventilation types. *Science of the Total Environment*, *668*, 56-66. https://doi.org/10.1016/j.scitotenv.2019.02.316

Kanniah, K. D., Kamarul Zaman, N. A. F., Kaskaoutis, D. G., & Latif, M. T. (2020). COVID-19's impact on the atmospheric environment in the Southeast Asia region. *Science of the Total Environment*, *736*, 139658. https://doi.org/10.1016/j.scitotenv.2020.139658

Karagulian, F., Belis, C. A., Dora, C. F. C., Pruss-Ustun, A., Bonjour, S., Adair-Rohani, H., & Amann, M. (2015). Contributions to cities' ambient particulate matter (PM): a systematic review of local source contributions at global level. . *Atmospheric Environment*, *120*, 475-483. https://www.sciencedirect.com/science/article/pii/S1352231015303320

Karottki, D. G., Spilak, M., Frederiksen, M., Gunnarsen, L., Brauner, E. V., Kolarik, B., Andersen, Z. J., Sigsgaard, T., Barregard, L., Strandberg, B., Sallsten, G., Moller, P., & Loft, S. (2013). An indoor air filtration study in homes of elderly: cardiovascular and respiratory effects of exposure to particulate matter. *Environmental Health: A Global Access Science Source*, *12*, 116. https://doi.org/10.1186/1476-069X-12-116

Keidel, D., Anto, J. M., Basagana, X., Bono, R., Burte, E., Carsin, A. E., Forsberg, B., Fuertes, E., Galobardes, B., Heinrich, J., de Hoogh, K., Jarvis, D., Kunzli, N., Leynaert, B., Marcon, A., Le Moual, N., de Nazelle, A., Schindler, C., Siroux, V., . . . Probst-Hensch, N. (2019). The Role of Socioeconomic Status in the Association of Lung Function and Air Pollution-A Pooled Analysis of Three Adult ESCAPE Cohorts. *International Journal of Environmental Research & Public Health [Electronic Resource]*, *16*(11). https://doi.org/10.3390/ijerph16111901

Kelly, F., & Fussell, J. C. (2019). Improving indoor air quality, health and performance within environments where people live, travel, learn and work. *Atmospheric Environment*, *200*, 90-109. https://doi.org/https://www.sciencedirect.com/science/article/pii/S1352231018308410

Kenfield, S. A., Wei, E. K., Stampfer, M. J., Rosner, B. A., & Colditz, G. A. (2008). Comparison of aspects of smoking among the four histological types of lung cancer. *Tobacco Control*, *17*(3), 198-204. https://doi.org/10.1136/tc.2007.022582

Kim, S., Yang, J., Park, J., Song, I., Kim, D. G., Jeon, K., Kim, H., & Yi, S. M. (2022). Health effects of PM(2.5) constituents and source contributions in major metropolitan cities, South Korea. *Environmental Science & Pollution Research*, *29*(55), 82873-82887. https://doi.org/10.1007/s11356-022-21592-1

Kinney, P. L., & Lippmann, M. (2000). Respiratory effects of seasonal exposures to ozone and particles. *Archives of Environmental Health*, *55*(3), 210-216. https://www.tandfonline.com/doi/abs/10.1080/00039890009603408

Klepeis, N. E., Nelson, W. C., Ott, W. R., Robinson, J. P., Tsang, A. M., Switzer, P., Behar, J. V., Hern, S. C., & Engelmann, W. H. (2001). The National Human Activity Pattern Survey (NHAPS): a resource for assessing exposure to environmental pollutants. *Journal of Exposure Analysis and Environmental Epidemiology*, *11*(3), 231-252. https://doi.org/10.1038/sj.jea.7500165

Knoke, J. D., Burns, D. M., & Thun, M. J. (2008). The change in excess risk of lung cancer attributable to smoking following smoking cessation: an examination of different analytic approaches using CPS-I data. *Cancer Causes Control*, *19*(2), 207-219. https://doi.org/10.1007/s10552-007-9086-5

Krasniqi, J. (2020). Covid 19 Pandemic Case Study: Kosovo. https://eu.boell.org/sites/default/files/2020-12/20201209-HB-papers-kosovo-A4-01.pdf

Krewski, D., Burnett, R. T., Goldberg, M. S., Hoover, B. K., Siemiatycki, J., Jerrett, M., Abrahamowicz, M., & White, W. H. (2003). Overview of the Reanalysis of the Harvard Six Cities Study and American Cancer Society study of particulate air pollution and mortality [Review]. *Journal of Toxicology* *and Environmental Health - Part A*, *66*(16-19), 1507-1551. https://doi.org/http://dx.doi.org/10.1080/15287390306424

Kumari, P., & Toshniwal, D. (2020). Impact of lockdown measures during COVID-19 on air quality- A case study of India. *International Journal of Environmental Health Research*, 1-8. https://doi.org/10.1080/09603123.2020.1778646

Laden, F., Schwartz, J., Speizer, F. E., & Dockery, D. W. (2006). Reduction in fine particulate air pollution and mortality: Extended follow-up of the Harvard Six Cities study. *American Journal of Respiratory & Critical Care Medicine*, *173*(6), 667-672. https://doi.org/10.1164/rccm.200503-443OC

Laumbach, R., Meng, Q., & Kipen, H. (2015). What can individuals do to reduce personal health risks from air pollution? *J Thorac Dis*, *7*(1), 96-107. https://doi.org/10.3978/j.issn.2072-1439.2014.12.21

Leavitt, M. (2004). *Advisory Council on Clean Air Compliance Analysis Response to Agency Request on Cessation Lag*. Retrieved from https://nepis.epa.gov

Leksell, I., & Rabl, A. (2001). Air pollution and mortality: quantification and valuation of years of life lost. *Risk Analysis*, *21*(5), 843-857. https://doi.org/10.1111/0272-4332.215156

Li, J., Mattewal, S.K., Patel, S., Biswas, P. (2020). Evaluation of Nine Low-cost-sensor-based Particle Matter Monitors. *Aerosol and Air Quality Research*, *20*, 254-270. https://aaqr.org/articles/aaqr-18-12-lcs-0485

Li, X., Chen, H., & Li, Y. (2020). The effect of air pollution on children's migration with parents: evidence from China. *Environmental Science & Pollution Research*, *27*(11), 12499-12513. https://doi.org/10.1007/s11356-020-07831-3

Liang, F., Lu, M., Keener, T. C., Liu, Z., & Khang, S. J. (2005). The organic composition of diesel particulate matter, diesel fuel and engine oil of a non-road diesel generator. *Journal of Environmental Monitoring*, *7*(10), 983-988. https://doi.org/10.1039/b504728e

Liang, L., Gong, P., Cong, N., Li, Z., Zhao, Y., & Chen, Y. (2019). Assessment of personal exposure to particulate air pollution: the first result of City Health Outlook (CHO) project. *BMC Public Health*, *19*(1), 711. https://doi.org/10.1186/s12889-019-7022-8

Liang, Z., Yang, Y., Li, J., Zhu, X., Ruan, Z., Chen, S., Huang, G., Lin, H., Zhou, J. Y., & Zhao, Q. (2019). Migrant population is more vulnerable to the effect of air pollution on preterm birth: Results from a birth cohort study in seven Chinese cities. *International Journal of Hygiene & Environmental Health*, *222*(7), 1047-1053. https://doi.org/10.1016/j.ijheh.2019.07.004

Lim, J. M., Jeong, J. H., Lee, J. H., Moon, J. H., Chung, Y. S., & Kim, K. H. (2011). The analysis of PM2. 5 and associated elements and their indoor/outdoor pollution status in an urban area. *Indoor Air*, *21*(2), 145-155. https://onlinelibrary.wiley.com/doi/10.1111/j.1600-0668.2010.00691.x

Lin, C., Hu, D., Jia, X., Chen, J., Deng, F., Guo, X., Heal, M. R., Cowie, H., Wilkinson, P., Miller, M. R., & Loh, M. (2020). The relationship between personal exposure and ambient PM(2.5) and black carbon in Beijing. *Science of the Total Environment*, *737*, 139801. https://doi.org/10.1016/j.scitotenv.2020.139801

Lin, Y., Ramanathan, G., Zhu, Y., Yin, F., Rea, N. D., Lu, X., Tseng, C. H., Faull, K. F., Yoon, A. J., Jerrett, M., Zhu, T., Qiu, X., & Araujo, J. A. (2019). Pro-Oxidative and Pro-Inflammatory Effects After Traveling from Los Angeles to Beijing: A Biomarker-Based Natural Experiment. *Circulation.*, *20*. https://doi.org/http://dx.doi.org/10.1161/CIRCULATIONAHA.119.042054

Liu, C., Chen, R., Sera, F., Vicedo-Cabrera, A. M., Guo, Y., Tong, S., Coelho, M., Saldiva, P. H. N., Lavigne, E., Matus, P., Valdes Ortega, N., Osorio Garcia, S., Pascal, M., Stafoggia, M., Scortichini, M., Hashizume, M., Honda, Y., Hurtado-Diaz, M., Cruz, J., . . . Kan, H. (2019). Ambient Particulate Air Pollution and Daily Mortality in 652 Cities. *N Engl J Med*, *381*(8), 705-715. https://doi.org/10.1056/NEJMoa1817364

Liu, J. J., Wang, F., Liu, H., Wei, Y. B., Li, H., Yue, J., Que, J., Degenhardt, L., Lappin, J., Lu, L., Bao, Y., & Wang, J. (2019). Association of ambient fine particulate matter with increased emergency ambulance dispatches for psychiatric emergencies: a time-series analysis [Conference Abstract]. *The Lancet*, *394 (Supplement 1)*, S7. https://doi.org/http://dx.doi.org/10.1016/S0140-6736%2819%2932343-8

Liu, S., Wu, T., Wang, Q., Zhang, Y., Tian, J., Ran, W., & Cao, J. (2023). High time-resolution source apportionment and health risk assessment for PM(2.5)-bound elements at an industrial city in northwest China. *Science of the Total Environment*, *870*, 161907. https://doi.org/10.1016/j.scitotenv.2023.161907

Lleras-Muney, A. (2010). The Needs of the Army: Using Compulsory Relocation in the Military to Estimate the Effect of Air Pollutants on Children's Health. *Journal of Human Resources*, *45*. https://doi.org/10.1353/jhr.2010.0016

Lopatin, O. P. (2020). Phenomenology of nitrogen oxides formation in a gas-diesel engine. *Journal of Physics: Conference Series*, *1515*. https://doi.org/10.1088/1742-6596/1515/4/042009

Lozano, R., Naghavi, M., Foreman, K., Lim, S., Shibuya, K., Aboyans, V., Abraham, J., Adair, T., Aggarwal, R., Ahn, S. Y., Alvarado, M., Anderson, H. R., Anderson, L. M., Andrews, K. G., Atkinson, C., Baddour, L. M., Barker-Collo, S., Bartels, D. H., Bell, M. L., . . . Memish, Z. A. (2012). Global and regional mortality from 235 causes of death for 20 age groups in 1990 and 2010: a systematic analysis for the Global Burden of Disease Study 2010. *Lancet*, *380*(9859), 2095-2128. https://doi.org/10.1016/s0140-6736(12)61728-0

Lynn, D. (2016). *Breathless in Jakarta - A Cautionary Tale*. Retrieved April 11, 2023 from https://afsa.org/breathless-jakarta-cautionary-tale

MacNeill, M., Wallace, L., Kearney, J., Allen, R., Van Ryswyk, K., Judek, S., Xu, X., & Wheeler, A. (2012). Factors influencing variability in the infiltration of PM2. 5 mass and its components. *Atmospheric Environment*, *61*, 518-532.

Madsen, C., Gehring, U., Walker, S. E., Brunekreef, B., Stigum, H., Naess, O., & Nafstad, P. (2010). Ambient air pollution exposure, residential mobility and term birth weight in Oslo, Norway. *Environ Res*, *110*(4), 363-371. https://doi.org/10.1016/j.envres.2010.02.005

Mahato, S., Pal, S., & Ghosh, K. G. (2020). Effect of lockdown amid COVID-19 pandemic on air quality of the megacity Delhi, India. *Science of the Total Environment*, *730*, 139086. https://doi.org/10.1016/j.scitotenv.2020.139086

Mannan, M., & Al-Ghamdi, S. G. (2021). Indoor Air Quality in Buildings: A Comprehensive Review on the Factors Influencing Air Pollution in Residential and Commercial Structure. *International Journal of Environmental Research & Public Health [Electronic Resource]*, *18*(6). https://doi.org/10.3390/ijerph18063276

McDuffie, E. E., Martin, R. V., Spadaro, J. V., Burnett, R., Smith, S. J., O'Rourke, P., Hammer, M. S., van Donkelaar, A., Bindle, L., Shah, V., Jaegle, L., Luo, G., Yu, F., Adeniran, J. A., Lin, J., & Brauer, M. (2021). Source sector and fuel contributions to ambient PM(2.5) and attributable mortality across multiple spatial scales. *Nature communications*, *12*(1), 3594. https://doi.org/10.1038/s41467-021-23853-y

McNamara, M. L., Thornburg, J., Semmens, E. O., Ward, T. J., & Noonan, C. W. (2017). Reducing indoor air pollutants with air filtration units in wood stove homes. *Science of the Total Environment*, *592*, 488-494. https://doi.org/10.1016/j.scitotenv.2017.03.111

Meng, J., Li, C., Martin, R. V., van Donkelaar, A., Hystad, P., & Brauer, M. (2019). Estimated Long-Term (1981-2016) Concentrations of Ambient Fine Particulate Matter across North America from Chemical Transport Modeling, Satellite Remote Sensing, and Ground-Based Measurements. *Environmental Science & Technology*, *53*(9), 5071-5079. https://doi.org/10.1021/acs.est.8b06875

Meredith, S. (2023). *Air pollution around the world: data is key* United States Department of State Retrieved from https://www.state.gov/dipnote/air-pollution-data

Militello-Hourigan, R., & Miller, S. (2018). The impacts of cooking and an assessment of indoor air quality in Colorado passive and tightly constructed homes. *Building and Environment*, *144*, 573-582. https://doi.org/https://doi.org/10.1016/j.buildenv.2018.08.044

Miller, B. G., & Hurley, J. F. (2003). Life table methods for quantitative impact assessments in chronic mortality. *Journal of Epidemiology & Community Health*, *57*(3), 200-206. https://doi.org/10.1136/jech.57.3.200

Moher, D., Liberati, A., Tetzlaff, J., Altman, D. G., & Group, P. (2009). Preferred reporting items for systematic reviews and meta-analyses: the PRISMA statement. *BMJ*, *339*, b2535. https://doi.org/10.1136/bmj.b2535

Mu, L., Liu, Z. Y., Li, Y. Y., Li, X. M., Li, X. F., Liu, T., Feng, C. Y., & Jiang, X. (2023). [Source Analysis and Health Risk Assessment of PAHs in PM(2.5), Luliang City]. *Huan Jing Ke Xue*, *44*(12), 6508-6517. https://doi.org/10.13227/j.hjkx.202210067

National Academies of Science. (2021). *Standing Committee on Medical and Epidemiological Aspects of Air Pollution on U.S. Government Employees and their Families*. https://www.nationalacademies.org/our-work/standing-committee-on-medical-and-epidemiological-aspects-of-air-pollution-on-us-government-employees-and-their-families

Padro-Martinez, L. T., Owusu, E., Reisner, E., Zamore, W., Simon, M. C., Mwamburi, M., Brown, C. A., Chung, M., Brugge, D., & Durant, J. L. (2015). A Randomized Cross-over Air Filtration Intervention Trial for Reducing Cardiovascular Health Risks in Residents of Public Housing near a Highway. *International Journal of Environmental Research & Public Health [Electronic Resource]*, *12*(7), 7814-7838. https://doi.org/https://dx.doi.org/10.3390/ijerph120707814

Pant, P., Habib, G., Marshall, J. D., & Peltier, R. E. (2017). PM(2.5) exposure in highly polluted cities: A case study from New Delhi, India. *Environ Res*, *156*, 167-174. https://doi.org/10.1016/j.envres.2017.03.024

Park, M., Joo, H. S., Lee, K., Jang, M., Kim, S. D., Kim, I., Borlaza, L. J. S., Lim, H., Shin, H., Chung, K. H., Choi, Y. H., Park, S. G., Bae, M. S., Lee, J., Song, H., & Park, K. (2018). Differential toxicities of fine particulate matters from various sources. *Sci Rep*, *8*(1), 17007. https://doi.org/10.1038/s41598-018-35398-0

Pereira, G., Bracken, M. B., & Bell, M. L. (2016). Particulate air pollution, fetal growth and gestational length: The influence of residential mobility in pregnancy. *Environ Res*, *147*, 269-274. https://doi.org/10.1016/j.envres.2016.02.001

Pope, C. A., 3rd, Burnett, R. T., Thun, M. J., Calle, E. E., Krewski, D., Ito, K., & Thurston, G. D. (2002). Lung cancer, cardiopulmonary mortality, and long-term exposure to fine particulate air pollution. *JAMA*, *287*(9), 1132-1141. https://doi.org/10.1001/jama.287.9.1132

Pope, C. A., 3rd, Coleman, N., Pond, Z. A., & Burnett, R. T. (2020). Fine particulate air pollution and human mortality: 25+ years of cohort studies. *Environ Res*, *183*, 108924. https://doi.org/10.1016/j.envres.2019.108924

Pozzer, A., Anenberg, S. C., Dey, S., Haines, A., Lelieveld, J., & Chowdhury, S. (2023). Mortality Attributable to Ambient Air Pollution: A Review of Global Estimates. *GeoHealth*, *7*(1), e2022GH000711. https://doi.org/10.1029/2022GH000711

Rajagopalan, S., Al-Kindi, S. G., & Brook, R. D. (2018). Air Pollution and Cardiovascular Disease: JACC State-of-the-Art Review. *J Am Coll Cardiol*, *72*(17), 2054-2070. https://doi.org/10.1016/j.jacc.2018.07.099

Renzetti, G., Silvestre, G., D'Amario, C., Bottini, E., Gloria-Bottini, F., Bottini, N., Auais, A., Perez, M. K., & Piedimonte, G. (2009). Less air pollution leads to rapid reduction of airway inflammation and improved airway function in asthmatic children [Research Support, N.I.H., Extramural]. *Pediatrics*, *123*(3), 1051-1058. https://doi.org/https://dx.doi.org/10.1542/peds.2008-1153

Rich, D. Q. (2017). Accountability studies of air pollution and health effects: lessons learned and recommendations for future natural experiment opportunities [Review]. *Environment International*, *100*, 62-78. https://doi.org/https://dx.doi.org/10.1016/j.envint.2016.12.019

Rich, D. Q., Kipen, H. M., Huang, W., Wang, G., Wang, Y., Zhu, P., Ohman-Strickland, P., Hu, M., Philipp, C., Diehl, S. R., Lu, S. E., Tong, J., Gong, J., Thomas, D., Zhu, T., & Zhang, J. J. (2012). Association between changes in air pollution levels during the Beijing Olympics and biomarkers of inflammation and thrombosis in healthy young adults. *JAMA*, *307*(19), 2068-2078. https://doi.org/10.1001/jama.2012.3488

Rodriguez-Urrego, D., & Rodriguez-Urrego, L. (2020). Air quality during the COVID-19: PM2.5 analysis in the 50 most polluted capital cities in the world. *Environmental Pollution*, *266*(Pt 1), 115042. https://doi.org/10.1016/j.envpol.2020.115042

Saint Akadiri, S., Adewale Alola, A., Olasehinde-Williams, G., & Udom Etokakpan, M. (2020). The role of electricity consumption, globalization and economic growth in carbon dioxide emissions and its implications for environmental sustainability targets. *Science of the Total Environment*, *708*, 134653. https://doi.org/10.1016/j.scitotenv.2019.134653

Sakai, M., Sato, Y., Sato, S., Ihara, S., Onizuka, M., Sakakibara, Y., & Takahashi, H. (2004). Effect of relocating to areas of reduced atmospheric particulate matter levels on the human circulating leukocyte count. *J Appl Physiol (1985)*, *97*(5), 1774-1780. https://doi.org/10.1152/japplphysiol.00024.2004

Sane, J., Schmidt, T., Isla, N., Ibrahim, R., Boshevska, G., Mayigane, L. N., Perriat, D., Stauke, J., Esquevin, S., & Fehr, A. (2023). Key lessons learnt from COVID-19 intra-action reviews in the Republic of Moldova, Montenegro, Kosovo and North Macedonia 2020–2021: a qualitative study. *BMJ Open*, *13*(3), e066279. https://bmjopen.bmj.com/content/13/3/e066279.abstract

Sang, S., Chu, C., Zhang, T., Chen, H., & Yang, X. (2022). The global burden of disease attributable to ambient fine particulate matter in 204 countries and territories, 1990-2019: A systematic analysis of the Global Burden of Disease Study 2019. *Ecotoxicology & Environmental Safety*, *238*, 113588. https://doi.org/10.1016/j.ecoenv.2022.113588

Saucy, A., Gehring, U., Olmos, S., Delpierre, C., de Bont, J., Gruzieva, O., de Hoogh, K., Huss, A., Ljungman, P., Melen, E., Persson, A., Pieterson, I., Tewis, M., Yu, Z., Vermeulen, R., Vlaanderen, J., & Tonne, C. (2023). Effect of residential relocation on environmental exposures in European cohorts: An exposome-wide approach. *Environment International*, *173*, 107849. https://doi.org/10.1016/j.envint.2023.107849

Schaefer-McDaniel, N. (2016). *The Air We Breathe: Living with Air Pollution*. Retrieved April 11, 2023 from https://afsa.org/air-we-breathe-living-air-pollution

Shaddick, G., Thomas, M. L., Amini, H., Broday, D., Cohen, A., Frostad, J., Green, A., Gumy, S., Liu, Y., Martin, R. V., Pruss-Ustun, A., Simpson, D., van Donkelaar, A., & Brauer, M. (2018). Data Integration for the Assessment of Population Exposure to Ambient Air Pollution for Global Burden of Disease Assessment. *Environmental Science & Technology*, *52*(16), 9069-9078. https://doi.org/10.1021/acs.est.8b02864

Sharma, S., Zhang, M., Anshika, Gao, J., Zhang, H., & Kota, S. H. (2020). Effect of restricted emissions during COVID-19 on air quality in India. *Science of the Total Environment*, *728*, 138878. https://doi.org/10.1016/j.scitotenv.2020.138878

Shi, Z., Song, C., Liu, B., Lu, G., Xu, J., Van Vu, T., Elliott, R. J. R., Li, W., Bloss, W. J., & Harrison, R. M. (2021). Abrupt but smaller than expected changes in surface air quality attributable to COVID-19 lockdowns. *Sci Adv*, *7*(3). https://doi.org/10.1126/sciadv.abd6696

Shrestha, P. M., Humphrey, J. L., Carlton, E. J., Adgate, J. L., Barton, K. E., Root, E. D., & Miller, S. L. (2019). Impact of Outdoor Air Pollution on Indoor Air Quality in Low-Income Homes during Wildfire Seasons. *International Journal of Environmental Research & Public Health [Electronic Resource]*, *16*(19). https://doi.org/10.3390/ijerph16193535

Shrubsole, C., Narváez, R., & Altamirano-Medina, H. (2016). Impact of the new Chilean air-tightness regulation on indoor air pollution in dwellings with inefficient heating sources. *Proceedings of the 14th International Conference of Indoor Air Quality and Climate (Indoor Air 2016). 14*. https://discovery.ucl.ac.uk/id/eprint/1492997/

Singh, J., & Singh, J. (2020). COVID-19 and its impact on society. *Journal of Social Sciences and Humanities*, *2*(1). https://doi.org/https://papers.ssrn.com/sol3/papers.cfm?abstract_id=3567837

South Coast Air Quality Monitoring District. (2020). *Field evaluation APT Minima.* Retrieved 1/28/2022 from http://www.aqmd.gov/docs/default-source/aq-spec/field-evaluations/apt-minima---field-evaluation.pdf?sfvrsn=8

Spilak, M. P., Sigsgaard, T., Takai, H., & Zhang, G. (2016). A Comparison between Temperature-Controlled Laminar Airflow Device and a Room Air-Cleaner in Reducing Exposure to Particles While Asleep. *PLoS ONE*, *11*(11), e0166882. https://doi.org/10.1371/journal.pone.0166882

StataCorp. (2022). *Stata Statistical Software: Release 17*. In StataCorp LLC.

Tsao, C. W., Aday, A. W., Almarzooq, Z. I., Alonso, A., Beaton, A. Z., Bittencourt, M. S., Boehme, A. K., Buxton, A. E., Carson, A. P., Commodore-Mensah, Y., Elkind, M. S. V., Evenson, K. R., Eze-Nliam, C., Ferguson, J. F., Generoso, G., Ho, J. E., Kalani, R., Khan, S. S., Kissela, B. M., . . . Martin, S. S. (2022). Heart Disease and Stroke Statistics-2022 Update: A Report From the American Heart Association. *Circulation*, *145*(8), e153-e639. https://doi.org/10.1161/CIR.0000000000001052

United Nations. (2020). *International Migration 2019 Report* [Gray Literature]. https://migrationnetwork.un.org/resources/international-migration-2019-report

United States Census Bureau. (2021). *American Community Survey 5-Year Data (2009-2021)* https://doi.org/https://www.census.gov/data/developers/data-sets/acs-5year.html

United States Census Bureau. (2022). *Median Household Income*. Retrieved April 12, 2023 from https://www.census.gov/library/visualizations/2022/comm/median-household-income.html

United States Department of State. (2018). *Survey data from posts, unpublished data*.

United States Department of State. (2020). *Popular Topics - Medical Clearances*. Retrieved 12/5/2020 from https://www.state.gov/popular-topics-medical-clearances/

United States Department of State. (2022a). *Foreign Affairs Manual*. Retrieved from https://fam.state.gov/

United States Department of State. (2022b). *Global Talent Management Fact Sheet*. Retrieved from https://afsa.org/sites/default/files/1222_state_dept_hr_factsheet.pdf

United States Embassy in Nepal. (2020). *COVID-19 Information Page*. Retrieved 2020, August 11 from https://np.usembassy.gov/covid-19-information-2/

United States Environmental Protection Agency. (2004). *Advisory Council on Clean Air Compliance Analysis Response to Agency Request on Cessation Lag*. Retrieved from https://nepis.epa.gov/Exe/ZyPURL.cgi?Dockey=P100JMYX.txt

United States Environmental Protection Agency. (2018). *Air Quality Trends (2001-2018)*. https://www3.epa.gov/region9/air/trends/pm25-annual.html

United States Environmental Protection Agency. (2023a). *AirNOW Department of State*. Retrieved 2020, August 12 from https://www.airnow.gov/international/us-embassies-and-consulates/

United States Environmental Protection Agency. (2023b). *National Ambiernt Air Quality Standars (NAAQS) for PM*. Retrieved May 5, 2023 from https://www.epa.gov/pm-pollution/national-ambient-air-quality-standards-naaqs-pm

Venter, Z. S., Aunan, K., Chowdhury, S., & Lelieveld, J. (2020). COVID-19 lockdowns cause global air pollution declines. *Proceedings of the National Academy of Sciences of the United States of America*. https://doi.org/10.1073/pnas.2006853117

Vilcassim, M. J. R., Thurston, G. D., Chen, L. C., Lim, C. C., Saunders, E., Yao, Y., & Gordon, T. (2019). Exposure to air pollution is associated with adverse cardiopulmonary health effects in international travellers. *Journal of Travel Medicine*, *26*(5), 11. https://doi.org/https://dx.doi.org/10.1093/jtm/taz032

Walton, H. (2010). *Supporting paper to COMEAP 2010 report The Mortality Effects of Long Term Exposure to Particulate Air Pollution in the United Kingdom.* Retrieved from https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/304655/COMEAP_development_of_proposals_for_cessation_lags.pdf

Wang, F., Meng, D., Li, X., & Tan, J. (2016). Indoor-outdoor relationships of PM2.5 in four residential dwellings in winter in the Yangtze River Delta, China. *Environmental Pollution*, *215*, 280-289. https://doi.org/10.1016/j.envpol.2016.05.023

Wellenius, G. A., Burger, M. R., Coull, B. A., Schwartz, J., Suh, H. H., Koutrakis, P., Schlaug, G., Gold, D. R., & Mittleman, M. A. (2012). Ambient air pollution and the risk of acute ischemic stroke. *Arch Intern Med*, *172*(3), 229-234. https://doi.org/10.1001/archinternmed.2011.732

Wen, X. J., Balluz, L. S., Shire, J. D., Mokdad, A. H., & Kohl, H. W. (2009). Association of self-reported leisure-time physical inactivity with particulate matter 2.5 air pollution. *Journal of Environmental Health*, *72*(1), 40-44; quiz 45. https://www.ncbi.nlm.nih.gov/pubmed/19681386

Wheeler, A. J., Gibson, M. D., MacNeill, M., Ward, T. J., Wallace, L. A., Kuchta, J., Seaboyer, M., Dabek-Zlotorzynska, E., Guernsey, J. R., & Stieb, D. M. (2014). Impacts of air cleaners on indoor air quality in residences impacted by wood smoke. *Environmental Science & Technology*, *48*(20), 12157-12163. https://doi.org/10.1021/es503144h

Wong, E. (2013a). On Scale of 0 to 500, Beijing's Air Quality Tops 'Crazy Bad' at 755. *The New York Times*. https://www.nytimes.com/2013/01/13/science/earth/beijing-air-pollution-off-the-charts.html

Wong, E. (2013b). U.S. Embassy Stocks Up on Air Purifiers. *New York Times*. https://archive.nytimes.com/sinosphere.blogs.nytimes.com/2013/11/25/u-s-embassy-stocks-up-on-air-purifiers/

World Health Organization. (2020). *The top 10 causes of death*. Retrieved October 22, 2023 from https://www.who.int/news-room/fact-sheets/detail/the-top-10-causes-of-death

World Health Organization. (2021). *WHO global air quality guidelines: particulate matter (PM2.5 and PM10), ozone, nitrogen dioxide, sulfure dioxide and carbon monoxide*. Retrieved December 19, 2021 from https://apps.who.int/iris/handle/10665/345329

World Health Organization. (2022). *Air quality database*. Retrieved September 4, 2022 from https://www.who.int/data/gho/data/themes/air-pollution/who-air-quality-database

Wu, S., Deng, F., Hao, Y., Wang, X., Zheng, C., Lv, H., Lu, X., Wei, H., Huang, J., Qin, Y., Shima, M., & Guo, X. (2014). Fine particulate matter, temperature, and lung function in healthy adults: findings from the HVNR study [Research Support, Non-U.S. Gov't]. *Chemosphere*, *108*, 168-174. https://doi.org/https://dx.doi.org/10.1016/j.chemosphere.2014.01.032

Wu, S., Deng, F., Huang, J., Wang, H., Shima, M., Wang, X., Qin, Y., Zheng, C., Wei, H., Hao, Y., Lv, H., Lu, X., & Guo, X. (2013). Blood pressure changes and chemical constituents of particulate air pollution: results from the healthy volunteer natural relocation (HVNR) study. *Environmental Health Perspectives*, *121*(1), 66-72. https://doi.org/10.1289/ehp.1104812

Xiang, J., Hao, J., Austin, E., Shirai, J., & Seto, E. (2021). Residential cooking-related PM(2.5): Spatial-temporal variations under various intervention scenarios. *Build Environ*, *201*. https://doi.org/10.1016/j.buildenv.2021.108002

Xiang, J., Huang, C. H., Shirai, J., Liu, Y., Carmona, N., Zuidema, C., Austin, E., Gould, T., Larson, T., & Seto, E. (2021). Field measurements of PM2.5 infiltration factor and portable air cleaner effectiveness during wildfire episodes in US residences. *Science of the Total Environment*, *773*, 145642. https://doi.org/10.1016/j.scitotenv.2021.145642

Yang, S., Yuk, H., Yun, B. Y., Kim, Y. U., Wi, S., & Kim, S. (2022). Passive PM2.5 control plan of educational buildings by using airtight improvement technologies in South Korea. *Journal of Hazardous Materials*, *423*(Pt A), 126990. https://doi.org/10.1016/j.jhazmat.2021.126990

Yildiz, I., Acikkalp, E., Caliskan, H., & Mori, K. (2019). Environmental pollution cost analyses of biodiesel and diesel fuels for a diesel engine. *Journal of Environmental Management*, *243*, 218-226. https://doi.org/10.1016/j.jenvman.2019.05.002

Yip, F., Christensen, B., Sircar, K., Naeher, L., Bruce, N., Pennise, D., Lozier, M., Pilishvili, T., Farrar, J. L., & Stanistreet, D. (2017). Assessment of traditional and improved stove use on household air pollution and personal exposures in rural western Kenya. *Environment international*, *99*, 185-191. https://www.sciencedirect.com/science/article/pii/S0160412016308091?via%3Dihub

Yu, L., Kang, N., Wang, W., Guo, H., & Ji, J. (2020). Study on the Influence of Air Tightness of the Building Envelope on Indoor Particle Concentration. *Sustainability*, *12*(5). https://doi.org/https://doi.org/10.3390/su12051708

Zhao, L., Chen, C., Wang, P., Chen, Z., Cao, S., Wang, Q., Xie, G., Wan, Y., Wang, Y., & Lu, B. (2015). Influence of atmospheric fine particulate matter (PM2.5) pollution on indoor environment during winter in Beijing. *Building and Environment*, *87*, 283-291. https://doi.org/https://doi.org/10.1016/j.buildenv.2015.02.008

Zhou, B., Liu, T., Yi, S., Huang, Y., Guo, Y., Huang, S., Zhou, C., Zhou, R., & Cao, H. (2022). Reducing the Effectiveness of Ward Particulate Matter, Bacteria and Influenza Virus by Combining Two Complementary Air Purifiers. *International Journal of Environmental Research & Public Health [Electronic Resource]*, *19*(16). https://doi.org/10.3390/ijerph191610446

Zhu, L., & Wang, J. (2003). Sources and patterns of polycyclic aromatic hydrocarbons pollution in kitchen air, China. *Chemosphere*, *50*(5), 611-618.

Appendices

Appendix 1: Supplementary material: Health effects in people relocating between environments of differing ambient air pollution concentrations: A literature review

Supplementary Materials for

Health effects of changes in ambient air pollution among people relocating between environments of differing ambient air pollution concentrations: a literature review

Leslie Edwards[1], Paul Wilkinson[1], Gemma Rutter[2], Ai Milojevic[1]

[1]London School of Hygiene and Tropical Medicine, London, England, United Kingdom
[2]United States Embassy in Kathmandu, Nepal

Table A1: Search Strategies Using Medline, Global Health, and Embase Databases

Three Category Search

1. exp air pollution/ or exp air pollutants/ or exp particulate matter/ or exp traffic-related pollution/ or (air pollut* or particulate matter or black carbon or black smoke or PM or particles or traffic-related pollution).ti,ab.
2. exp observational study/ or military personnel/ or exp migrant/ or (exp transients/ and migrants/) or exp government employees/ or relocat*.mp. or (exp emigration/ and immigration/) or (exp emigrants/ and exp immigrants/) or ((residen* or population) adj3 (health or change* or mobility or move*)).mp. or relocat*.mp. or ((migration or district or area) adj5 (urban or rural)).mp. or deployment*.mp. or ((government or work) adj3 (remov* or transfer)).mp. or (military or soldier or student* or migrant or expatriate or diplomat* or deploy* or post-war or army or navy or naval or travel* or natural experiment or observational study).ti,ab.
3. exp asthma/ or pulmonary disease, chronic obstructive/ or exp cardiovascular/ or exp mortality/ or exp death/ or birth.mp or exp parturition/ or exp birth weight or (asthma or acute disease or pulmonary disease, chronic obstructive or cardiovascular or respiratory or mortality or death or cardiopulmonary).ti,ab.
4. 1 and 2 and 3
5. 4 not (animals not humans).sh.
6. limit 5 to english language
7. 6 and 1989:2020.(sa_year).
8. remove duplicates from 7

Appendix 2: Supplementary material: Personal exposure monitoring of $PM_{2.5}$ among US diplomats in Kathmandu during the COVID-19 lockdown, March to June 2020

Supplementary Materials for

Personal Exposure Monitoring of $PM_{2.5}$ Among US Diplomats in Nepal During the COVID-19 Lockdown, March to June 2020

Leslie Edwards[a], Gemma Rutter[b], Leslie Iverson, Laura Wilson[c], Tandeep S. Chad h[ad], Paul Wilkinson[a], Ai Milojevic[a]

[a]London School of Hygiene and Tropical Medicine, London, England, United Kingdom
[b]United States Embassy in Kathmandu, Nepal
[c]Johns Hopkins Bloomberg School of Public Health, Baltimore, Maryland, USA
[d]Applied Particle Technology, St. Louis, Missouri, USA

* Corresponding Author: lsh1514008@lshtm.ac.uk

Table of Contents

Table A.1 **Dates that COVID-Related Mitigation Measures Were Implemented and Dates of First and Second COVID Cases Identified in Nepal**

Date	Event
January 23	First COVID-19 case identified in Nepal
March 14	All trekking to Mt Everest halted and visa upon entry at Tribhuvan International Airport closed
March 18	Movie theatres, gyms, museums, and mass gatherings of more than 25 people halted in Kathmandu
March 20	Non-urgent surgeries postponed in Kathmandu
March 22	International inbound and outbound flights halted in Nepal
March 23	Second COVID-19 case identified in Nepal
March 24	Nationwide lockdown implemented and included cessation of non-essential government services, prohibition of driving per personal vehicles, and closure of shops that do not sell food, petrol, or other essential services
April 4	First case of locally acquired COVID-19 identified in Nepal
June 12	Nationwide easing of lockdown measures including allowing shops to reopen, allowed to drive personal vehicles, but public places including schools, malls, parks, conferences, and sporting events remain closed
July 21	Nationwide lockdown in Nepal ended

Table A.2 Demographic characteristics of four study participants

Characteristics	**K1**	**K2**	**K3**	**K4**
Sex	Male	Female	Female	Female
Age Group (years)	40-49	30-49	50-59	50-59
Workplace	Home and Embassy [1]	Embassy	Embassy	Embassy
Mode of Transportation in Commute to Work?	NA	Personal Car and Walk	Walk	Walk
Total No. Room Air Cleaners in Home	11	9	9	6
No. Blueair 605 (large)	2	2	2	1
No. Blueair 205 (small)	9	7	7	5
Room Air Cleaner in Bedroom	Yes	Yes	Yes	Yes
Room Air Cleaner in Living Room	Yes	Yes	Yes	Yes
Room Air Cleaner in Kitchen	No	Yes	Yes	No
Home has windows and doors that do not close tightly	Yes	Yes	Yes	Yes
Windows Sealed with Tape and Plastic Sheeting	No	Yes	No	Yes
Windows Sealed with Caulk	Yes	No	No	No
Net Square Footage of Personal Residence (ft^2)	2177	1680	1860	2037

[1] Participant worked from home in September 2019 and began to work at the US Embassy in January 2020

Table A.3 Summary statistics for ambient $PM_{2.5}$ hourly measurements at [A] the US Embassy and [B] the Phora Durbar Recreational Complex, Kathmandu, March 24-June 11 each year 2017-2020

[A] US Embassy	**Year**			
	2020	2019	2018	2017
No. Observations	1891	1862	1915	1912
Minimum	0	3	0	8
5%	7	18	18	21
25%	17	33	31	35
50%	26	49	43	48
75%	39	68	61	66
95%	93	110	118	122
Maximum	365	685	252	674

[B] Phora Durbar	**Year**			
	2020	2019	2018	2017
No. Observations	1911	1878	1893	1900
Minimum	0	7	4	10
5%	9	23	20	27
25%	19	39	35	42
50%	28	58	48	58
75%	40	79	69	81
95%	86	124	127	153
Maximum	183	309	290	776

Table A.4 Summary statistics for personal monitoring sessions for Participants K1, K2, K3 and K4 take before (B) COVID-19 lockdown period and during (D) lockdown

	K1 - B	K1 - D	K2 - B	K2- D	K3 - B	K3 - D	K4 - B	K4 - D
No. Observations	2838	2859	2810	2856	2880	2845	2878	2855
Minimum	0	0	0	0	0	0	0	0
5%	0	0	0	0	0	0	1	0
25%	0	0	0	0	0	0	1	0
50%	1	1	0	0	1	0	2	0
75%	4	7	0	0	8	0	10	0
95%	26	31	0	0	45	8	18	1
Maximum	56	221	46	7	130	319	26	9

Figure A.1 Beta Attenuation Monitors (BAMs) at the US Embassy in Kathmandu and at the Phora Durbar Recreational Complex in Kathmandu. The two sites are 4.5 km apart. Red circle indicates the area where the four study participants live.

Figure A.2 The APT Minima personal air sampler. The monitor is 3” x 2.75” x 1.25” (L x W x H) and weights 4.9 oz.

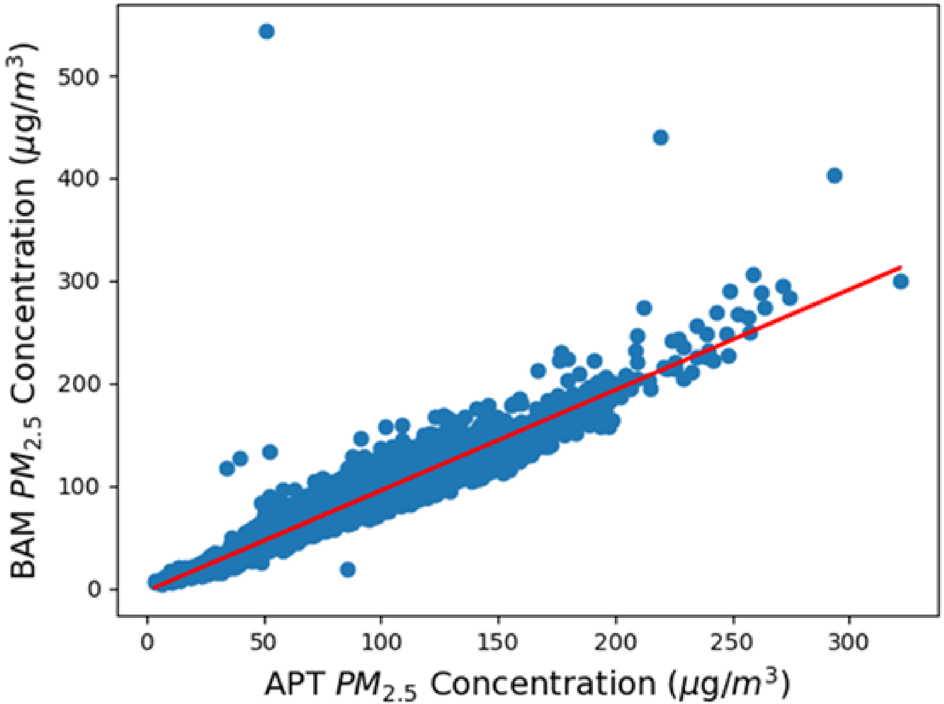


Figure A.3 Pairwise correlation between the APT Maxima (x-axis) and the BAM (y-axis) co-located at the Phora Durbar Recreation Center in Kathmandu. Slope and R^2 values were calculated by least squares method.

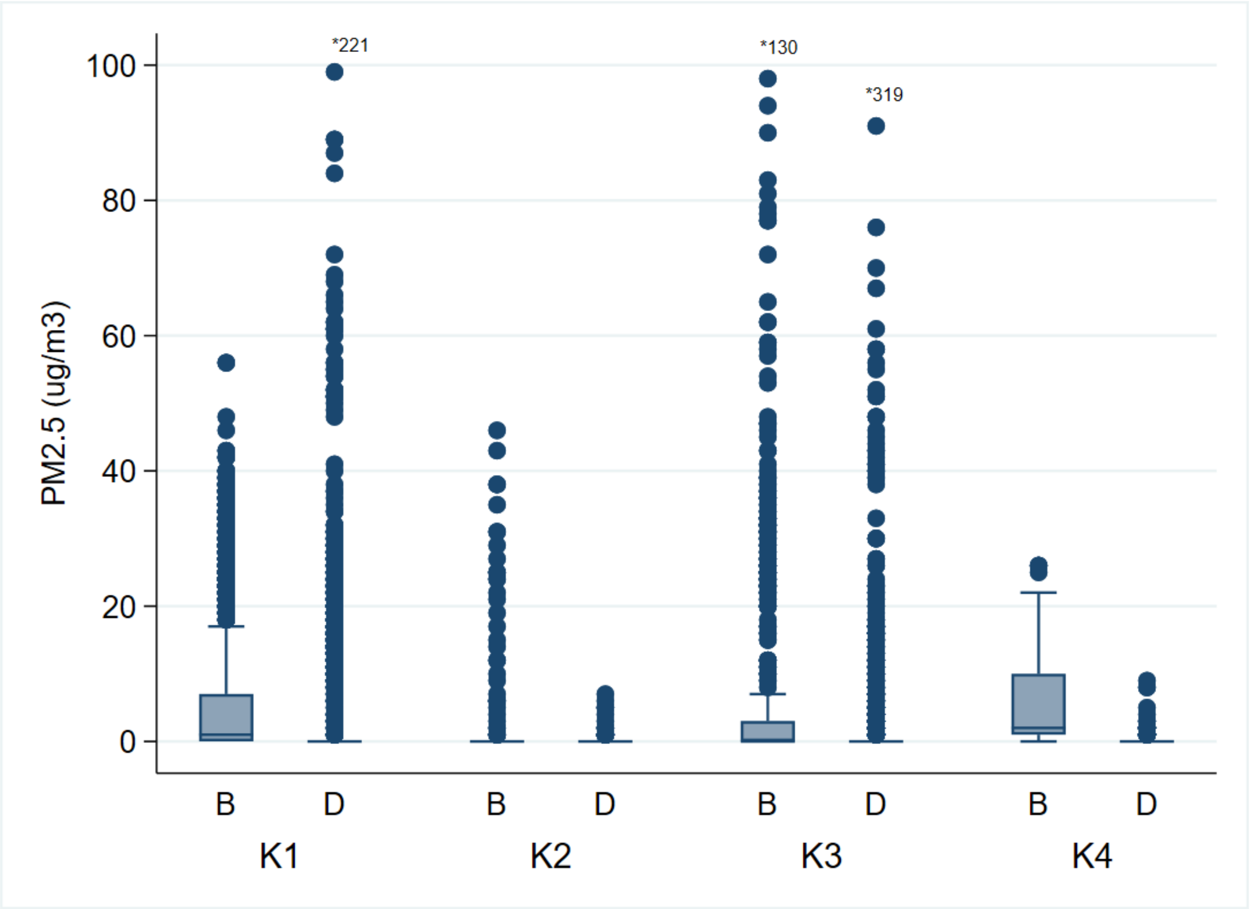


Figure A.4 Distribution of personal PM2.5 concentrations (µg/m^3) for study participants K1, K2, K3 and K4 before (B) COVID restrictions were implemented and during (D) COVID restrictions. The y-axis was truncated at 100 to allow for increased viewing of the box plots. Three monitoring sessions had values that exceeded the maximum y-axis value on this graph and those sessions were labelled with the highest recorded value for that session.

Appendix 3: Supplementary material: Impact of mitigation measures to improve home indoor air quality in Kathmandu, Nepal

Supplementary Materials

Impact of mitigation measures to improve home indoor air quality in Kathmandu, Nepal

Leslie Edwards[a]*, Paul Wilkinson[a], Gemma Rutter[b], Leslie Iverson[b], Ai Milojevic[a]

[a]London School of Hygiene and Tropical Medicine, London, England, United Kingdom
[b]United States Embassy in Kathmandu, Nepal

* Corresponding Author: Leslie.Edwards@lshtm.ac.uk

Table of Contents

Table A1. Summary of $PM_{2.5}$ exposure by microenvironment, includes 30 participants with all pre- and post-intervention measures

Pre-Intervention (31 monitoring sessions)

	Home – Indoors[1]	*Home – Cooking*	*Indoor Other*	*Embassy*	*Commute by Car*	*Outdoors*	*Missing*	*Overall*
$PM_{2.5}$ Mean (SD)	7.7 (7.0)	43.9 (33.9)	38.3 (53.6)	0.4 (0.5)	22.9 (11.6)	42.8 (24.6)	n/a	26.4 (32.5)
Ambient $PM_{2.5}$ Mean	44.8 (27.7)	58.3 (36.8)	37.6 (17.6)	55.6 (25.3)	39.9 (19.5)	46.0 (26.0)	43.9 (24.9)	45.7 (26.0)
# Participants in this ME	31	19	26	18	24	30	28	n/a
% Time in Location	49%	2%	9%	12%	3%	4%	21%	100%
Time in Microenvironment (hrs)	727.0 hr	26.7 hr	127.9 hr	174.7 hr	50.7 hr	63.4 hr	331.0 hr	1488.0 hr
Cumulative exposure	5229.3	1095.6	4395.5	99.9	1221.9	2563.4	n/a	15566.1
Cum. Exposure per person	178.4	35.3	141.7	3.2	39.4	83.1	n/a	488.4
Personal/Ambient Ratio	0.17	0.75	1.02	0.01	0.57	0.93	n/a	0.58

Post-Intervention (33 monitoring sessions)

	Home – Indoors[1]	*Home – Cooking*	*Indoor Other*	*Embassy*	*Commute by Car*	*Outdoors*	*Missing*	*Overall*
Mean (SD)	8.4 (10.1)	45.5 (19.8)	38.9 (36.5)	0.2 (0.5)	23.3 (14.8)	46.3 (31.2)	n/a	24.9 (28.0)
Ambient PM2.5 Mean	70.3 (26.8)	58.3 (47.2)	61.4 (32.6)	51.4 (23.5)	69.4 (31.4)	61.5 (32.5)	77.5 (41.5)	66.9 (33.6)
# Participants in this ME	33	15	23	26	27	28	17	n/a
% Time in Location	63%	2%	9%	9%	3%	4%	11%	100%
Time in Microenvironment (hrs)	997.0 hr	29.5 hr	135.3 hr	138.7 hr	49.6 hr	57.5 hr	179.7 hr	1584.0 hr
Cumulative exposure	7616.0	1492.3	4476.0	16.1	1334.2	2590.2	n/a	17524.8
Cum. Exposure per person	219.9	45.7	133.4	0.5	35.8	83.6	n/a	518.8
Personal/Ambient Ratio	0.12	0.78	0.63	<0.01	0.34	0.75	n/a	0.37

[1] Home – indoors category does not include periods of cooking which are separated and included under the heading “home – cooking”

[2] Ambient data derived from the data reported from the fixed site monitor (US Embassy or Phora Durbar) that was closest to each participants’ home during personal monitoring

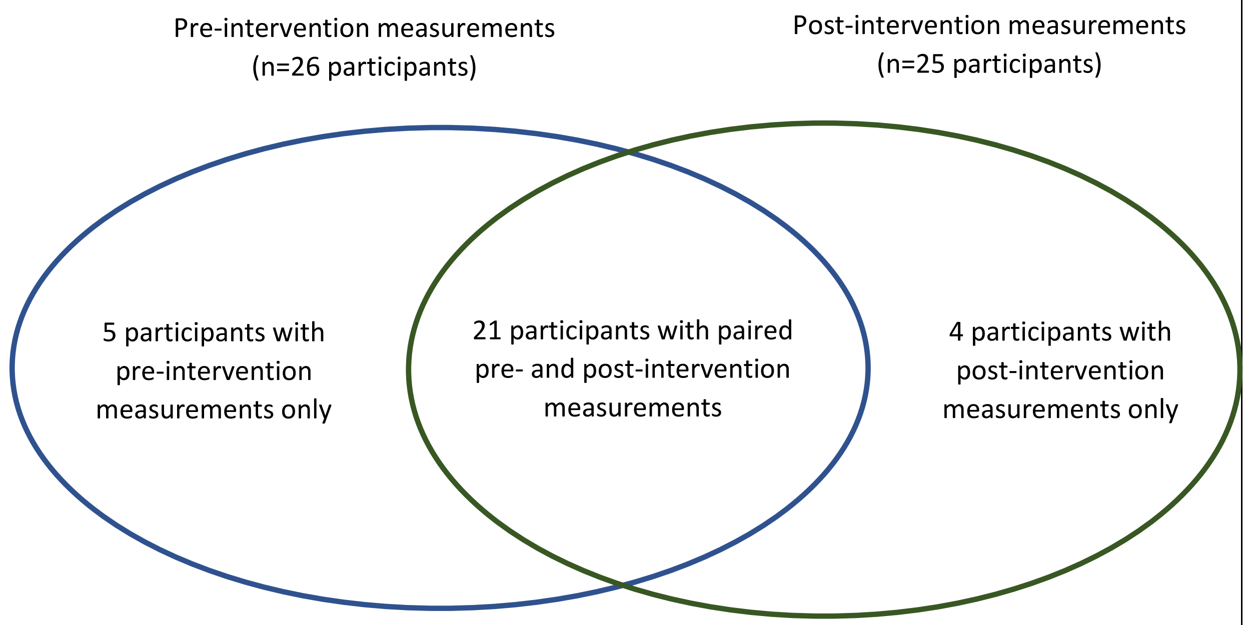


Figure A1. Summary of participants with personal monitoring recording periods.

Figure A2: Home in Kathmandu that is similar to the style, size, and construction of study participants' homes

Figure A3. The APT Minima personal air sampler. The monitor is 7.6cm x 7cm x 3.2cm (L x W x H) and weights 138.9g.

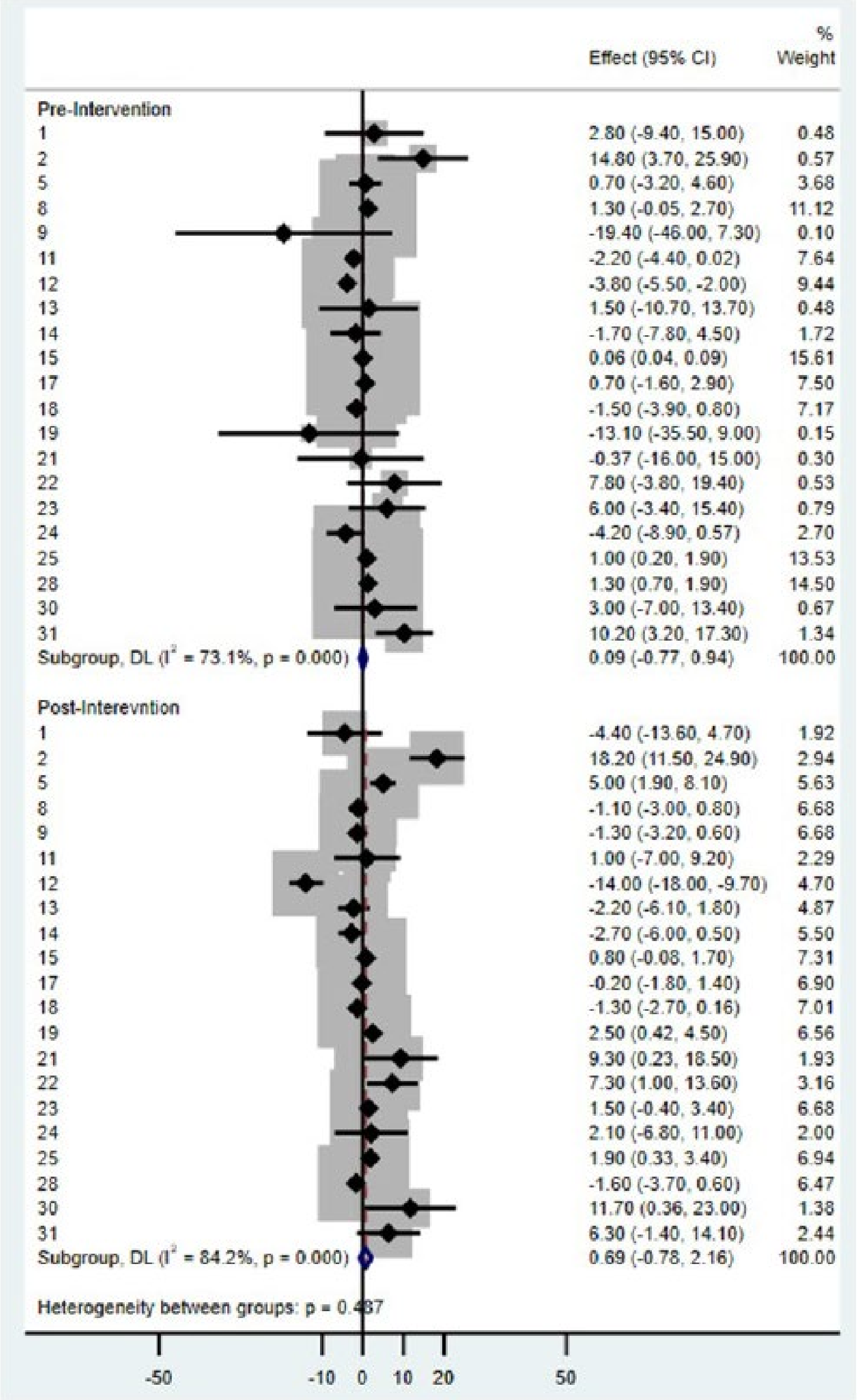


Figure A4: Meta-analysis of the dwelling specific y-intercepts of the indoor/outdoor (I/O) $PM_{2.5}$ ratio pre- and post-intervention, n=21.

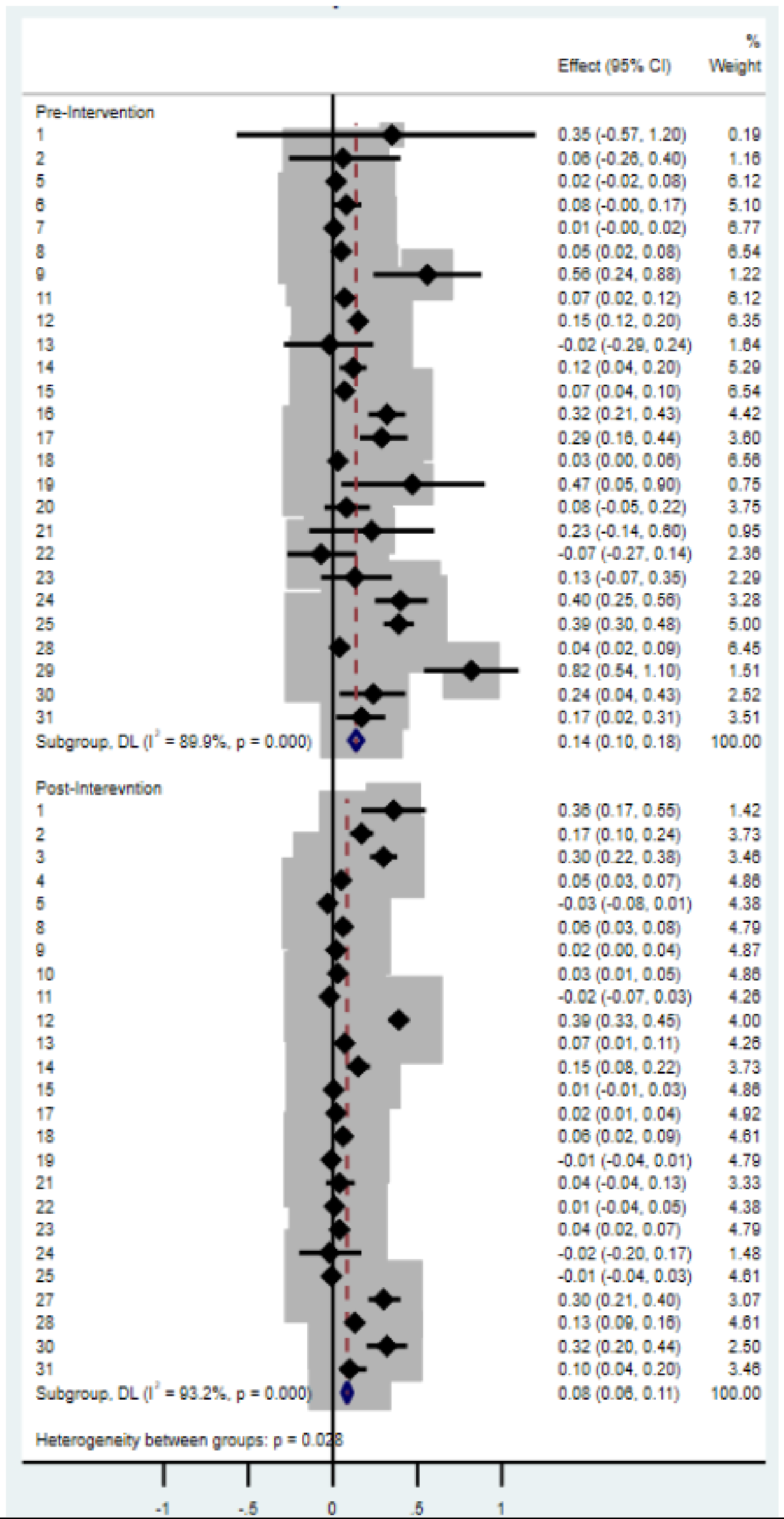


Figure A5. Meta-analysis of the dwelling-specific slopes of the indoor/outdoor (I/O) $PM_{2.5}$ ratio for all study participants, including those with unpaired data from pre- or post-intervention periods.

KATHMANDU - Personal Exposure Monitoring Questionnaire, v5

Complete this form before each of the 4 times that you wear them

Participant ID: Kat- __ __ __

1. Today's Date: ________(month)/_________(day)/____________(year)
2. Today will be the _____ time I will wear a monitor in this project (mark "X" on appropriate line)
   ___First (1) ___Second (2) ___Third (3) ___Fourth (4)

Home Environment

For the following questions, answer based on your home and activities in the last 1 week (7 days)

3. What brand of room air cleaners do you have in your house?
   a. Blue Air 205 b. Other (list) _______________

- How often did you use a room air cleaner at home in each of these rooms? (mark "X" for each room)

Room	Always	Sometimes	Never
4. Living Room			
5. Your Bedroom			
6. Kitchen			

7. Which setting did you use last week on the Room Air Cleaners?
   __3 (highest) __2 __1 (lowest) __0 (off)
8. Do any of the following attributes of the room air cleaners make you less likely to use them (mark "x" if yes):
   __ a. The sound is too loud
   __ b. Confusion about when/how to change the filters
   __ c. I don't think they work
   __ d. Other (list) ____
9. Does your home have any of the following (mark "X" if yes):
   __ a. Windows that don't close tightly or at all?
   __ b. Openings at the doorways that don't fully close?
   __ c. Doors and/or windows where extra efforts have been made to seal the openings to limit air pollution seeping inside? __ Yes __ No
   - If yes, describe in further detail (materials used, doors or windows sealed) ___________________
     ____
     ____

Daytime Activities/Work/School

For each of the following questions, answer based on your activities in the last 1 week (7 days)

10. Do you work at the US Embassy? __Yes __No
11. If yes to Q10 and you work in a site other than the main Embassy building, list it here ________________
12. Do you attend school? __Yes __No
13. If yes to Q12, list the school name ____
14. How did you travel to work/school and back (mark "X" if yes, you can choose more than 1 response):
    __a. drive personal vehicle __b. ride a shuttle bus __c. walk ___d. bicycle
    __e. take local taxi __f. other option (list)_________________________________
15. Have you worn any of the following masks or respirators outdoors to reduce air pollution exposure (mark "X" if yes)?
    __ a. N95 mask __b. Surgical mask __c. None __d. Other (list)__________________

Health Measurements (performed by Nurse or Other Health Unit Clinician)

16. ______ Heart Rate 17./18. ____/____ Blood Pressure (15 systolic/16 diastolic)
19. ______ L/min Peak Flow 20. ______% Oxygen Saturation

Only complete this section the first time you wear the monitors or if you have moved during the project:

20. Year of Birth: ______ 21.. Gender (mark "x" if yes): __Male __Female ___N/A
22. Agency you are affiliated with (State, USAID, etc): ___________________
23. Address at post: ____
24. Name of the neighborhood where you live _________________________

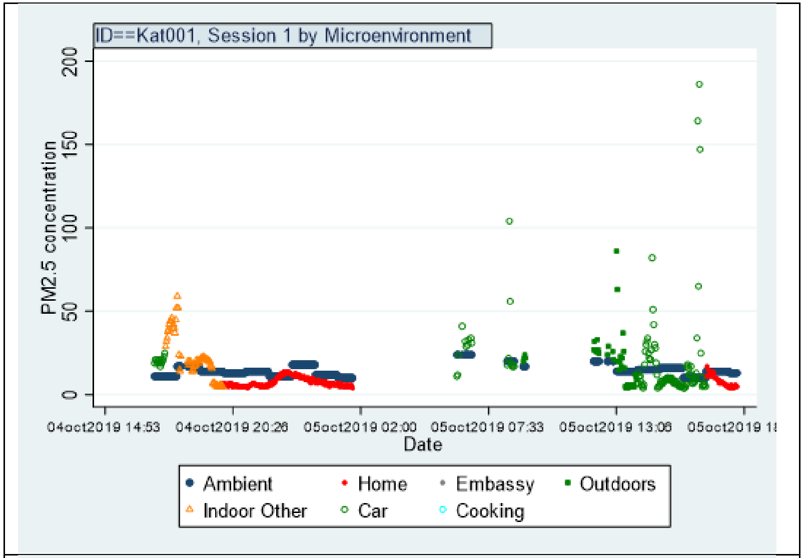
PM$_{2.5}$ Personal Exposure Monitoring Time Series Plots for Each Monitoring Session for Each of the 30 Participants

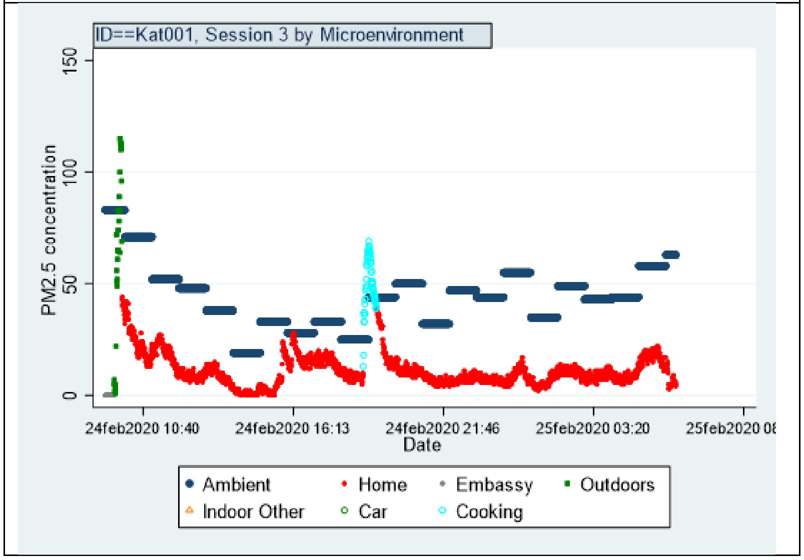
Kat 001

Did not work at the Embassy (spouse of Kat 002)

Excluded from intervention study results due to missing data

- Session 1, started 10/4/2019
    - 8 room air cleaners, no efforts to seal home
    - Duration of monitoring session = 22 hours
- Session 2, started 12/1/2019
    - Time activity diary is not available
- Session 3, started 2/24/2020
    - 10 room air cleaners, home sealed – children's rooms were sealed with plastic inside the home. Taped and caulked the windows in the main bedroom and living room
    - Duration of monitoring session = 20 hours





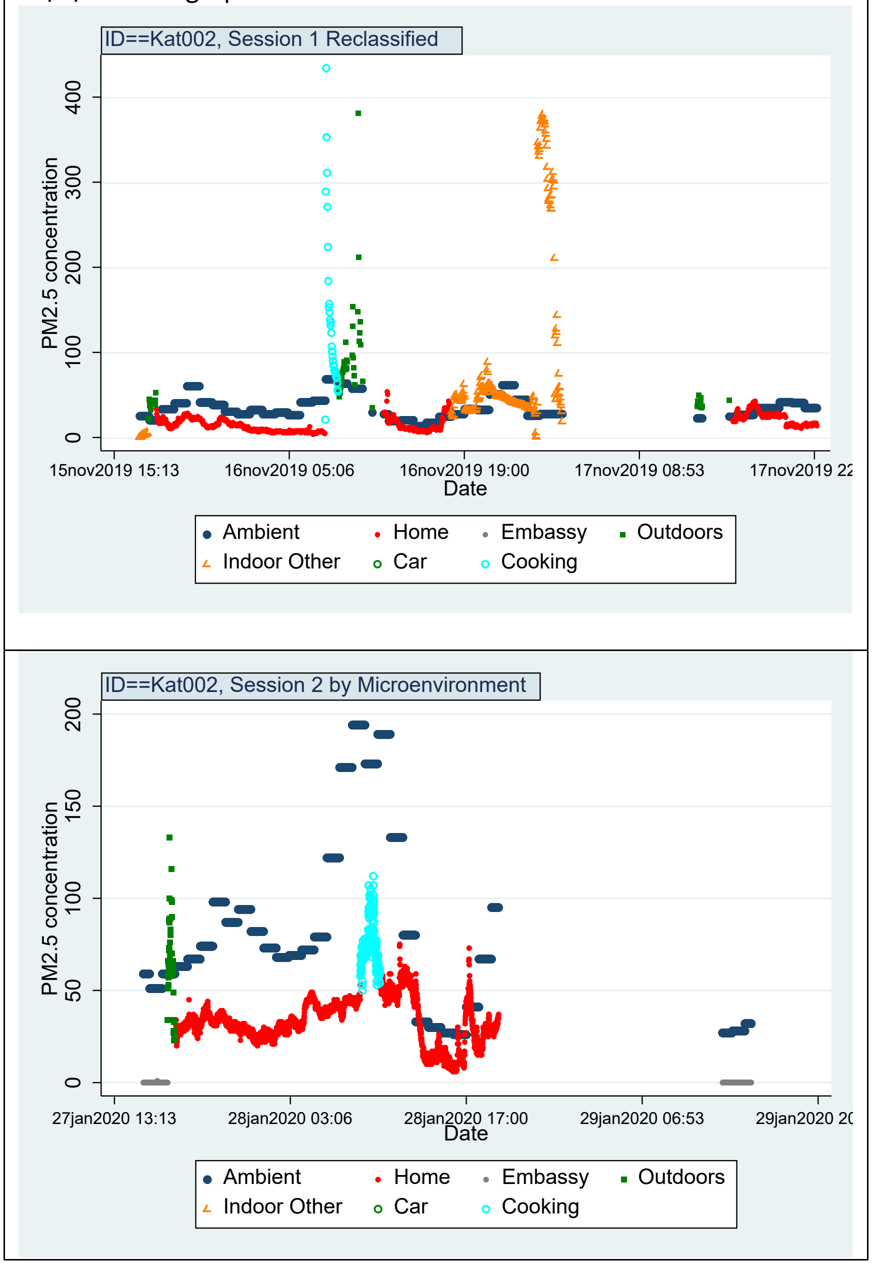
Kat 002

Did not work at the Embassy (spouse of Kat 001)

Excluded from intervention study results due to missing data

- Session 1, started Nov 15, 2019
  - 8 room air cleaners, no effort to seal home
  - Duration= 29 hours
- Session 2, started Jan 27, 2020
  - 10 room air cleaners, no effort to seal home
  - Duration = 25 hours

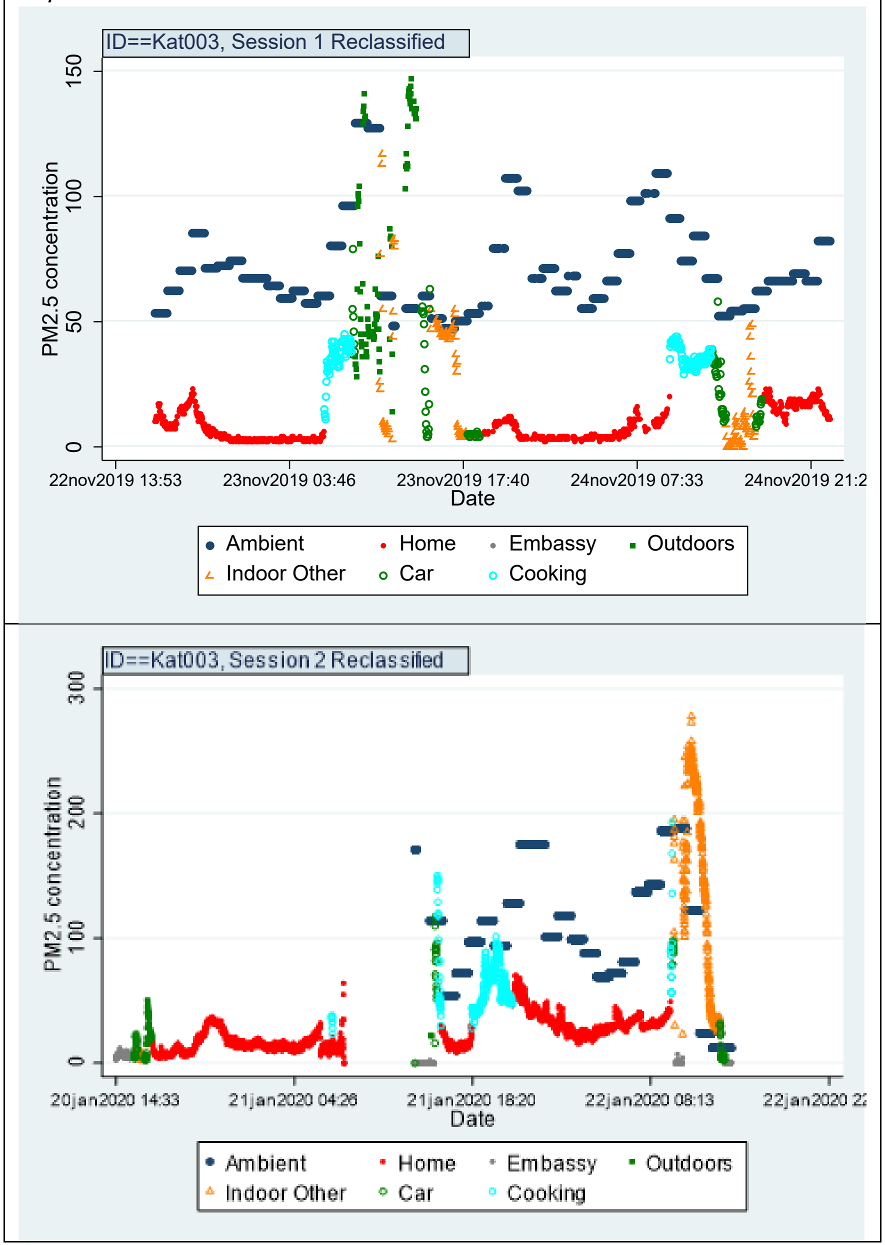
12/1/2021 IO graph



Kat 003

Did not work at the US Embassy

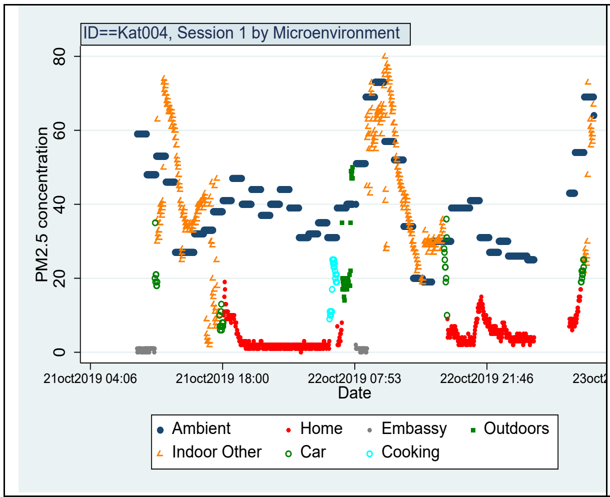
- Session 1, started Nov 22 2019
    - 8 room air cleaners, plastic sheets and duct tape applied on windows to seal gaps
    - Duration = 54 hours
- Session 2, started Jan 22, 2020
    - 10 room air cleaners, plastic sheets and duct tape applied on windows to seal gaps
    - Duration = 39 hours; 5.5 hours of missing data (1/21 820-1400)

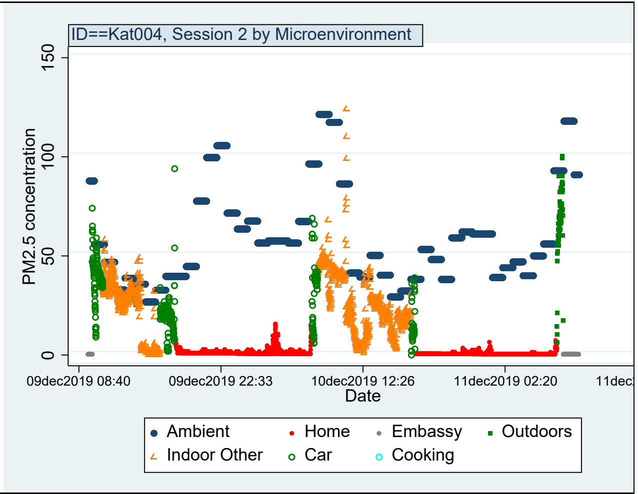

12/7

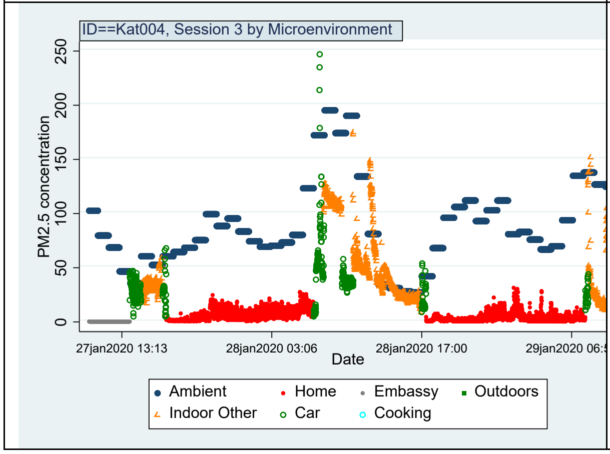
Kat 004

Did not work at the US Embassy

- Session 1, started Oct 21, 2019
    - 10 room air cleaners, plastic sheets and duct tape applied on windows to seal gaps
    - Duration = 23 hours
- Session 2, started Dec 11, 2019
    - 12 room air cleaners, plastic sheets and duct tape applied on windows to seal gaps
    - Duration= 37 hours
- Session 3, started Jan 27, 2020
    - 12 room air cleaners, plastic sheets and duct tape applied on windows to seal gaps
    - Duration = 37 hours







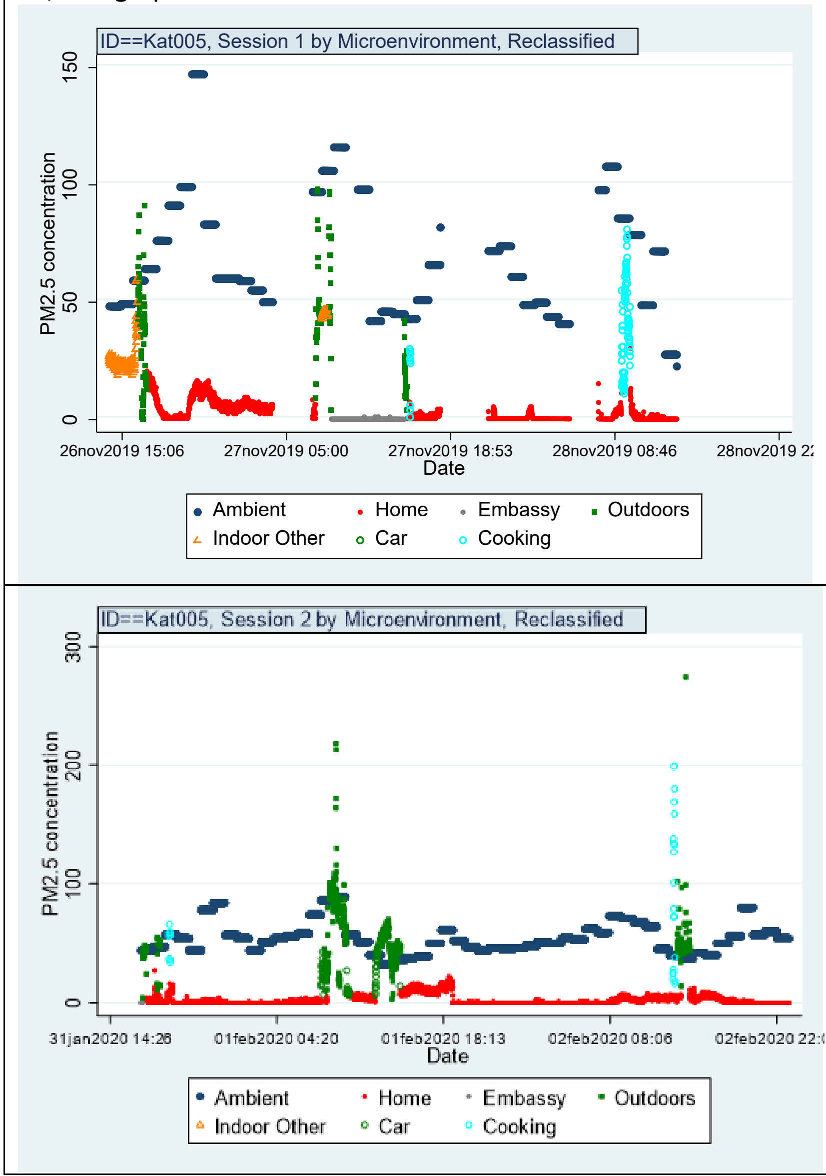
Kat 005

Excluded from analysis due to missing data

Worked at Embassy employee, often at off-site buildings

- Session 1, started Nov 16 2019
  - 10 RACs at home, no efforts to seal home
  - Duration= 31 hours
- Session 2, started Jan 31, 2020
  - 12 RACs at home, windows taped, and plastic used to seal windows
  - Duration= 54 hours

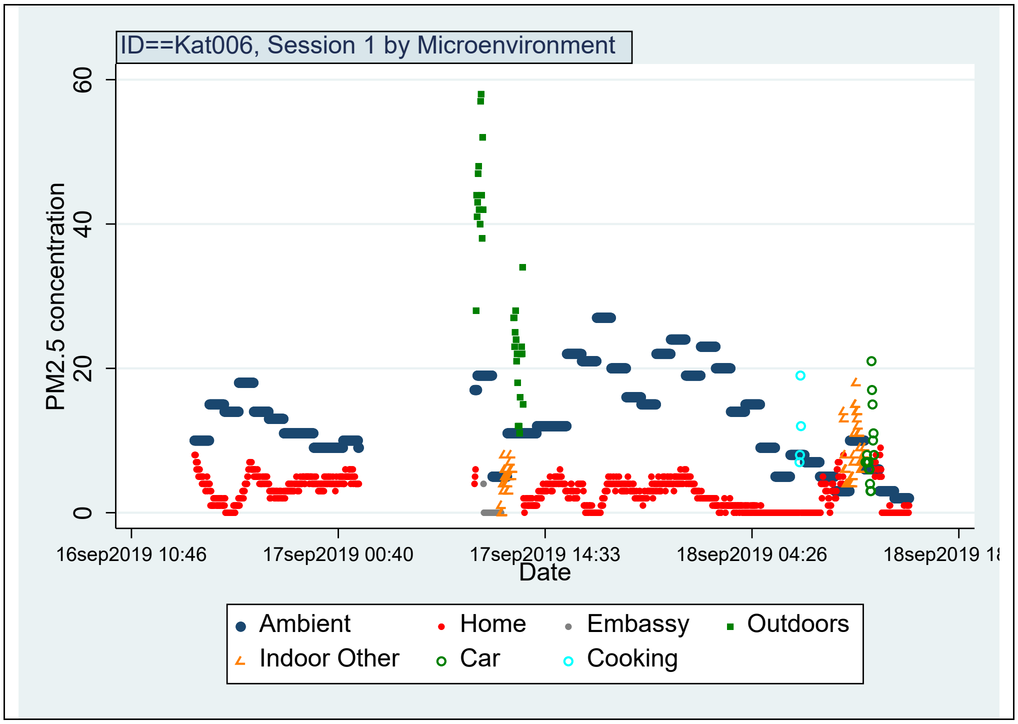
12/1 IO graph



Kat 006

Did not work at the US Embassy

- Session 1
  - 16 room air cleaners in the house
  - Duration = 45 hours

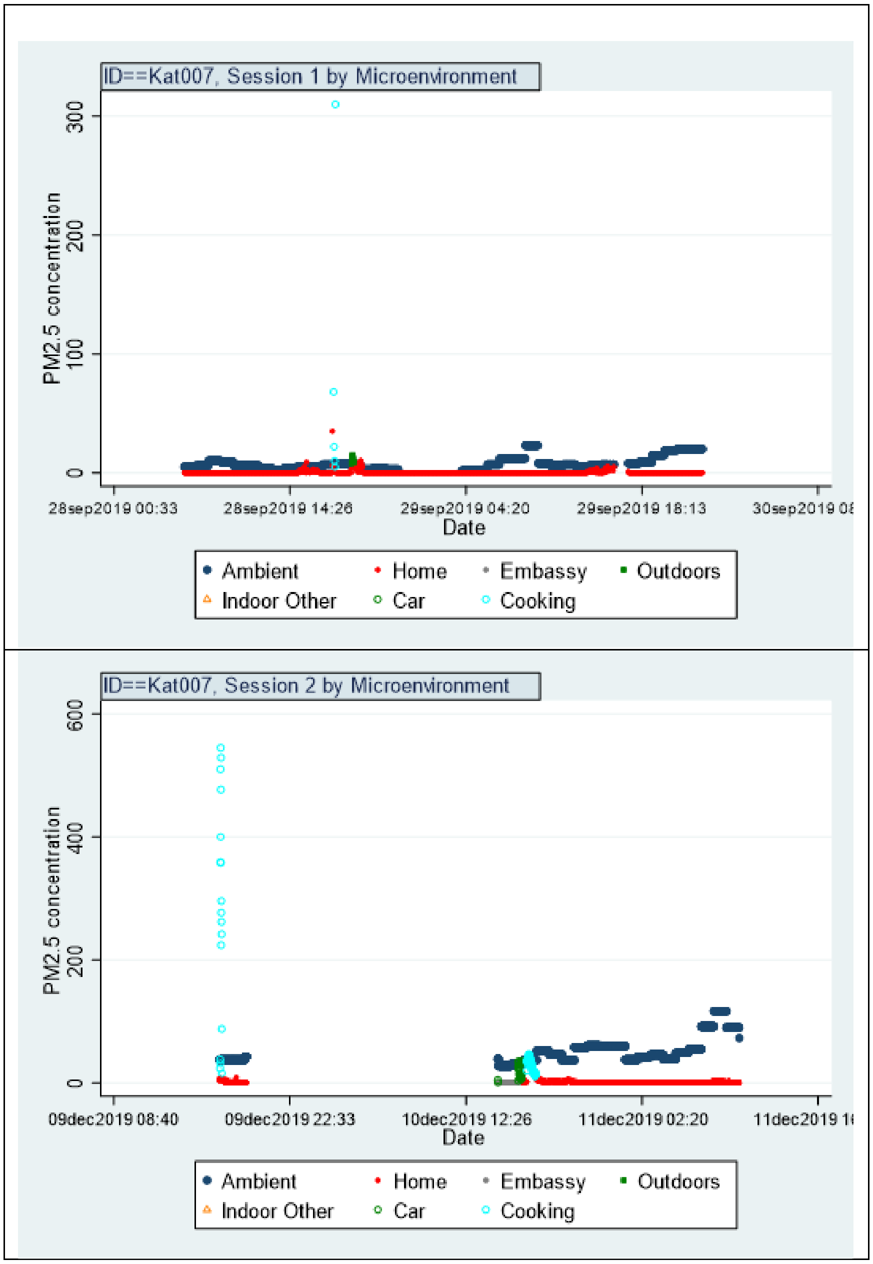


Kat 007

Worked at the US Embassy

Excluded from intervention study results due to missing data

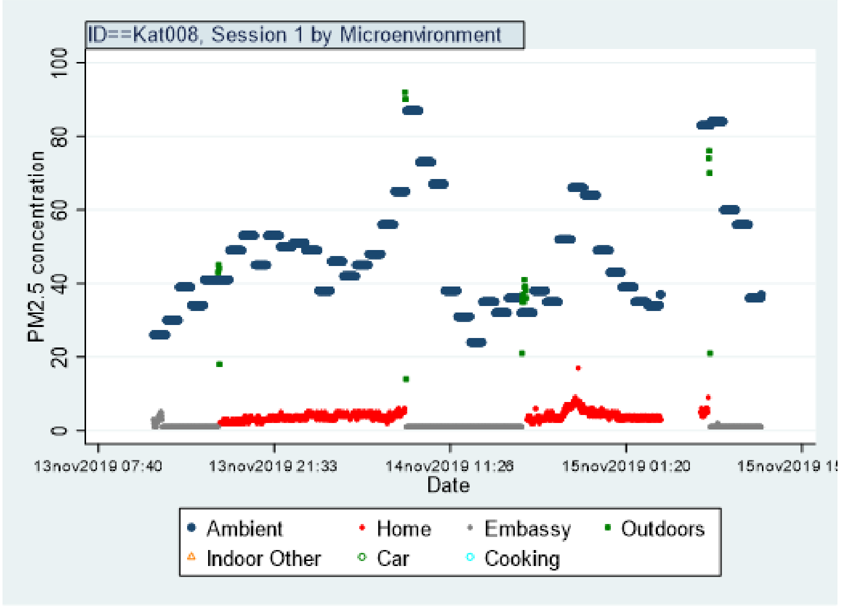
- Session 1, started Sep 28, 2019
    - 9 RACs at home, home sealed with caulk and weather stripping
    - Duration = 35 hours
- Session 2, started Dec 9, 2019
    - 9 RACs at home, home sealed with caulk and weather stripping (no change)
    - Duration = 19 hours

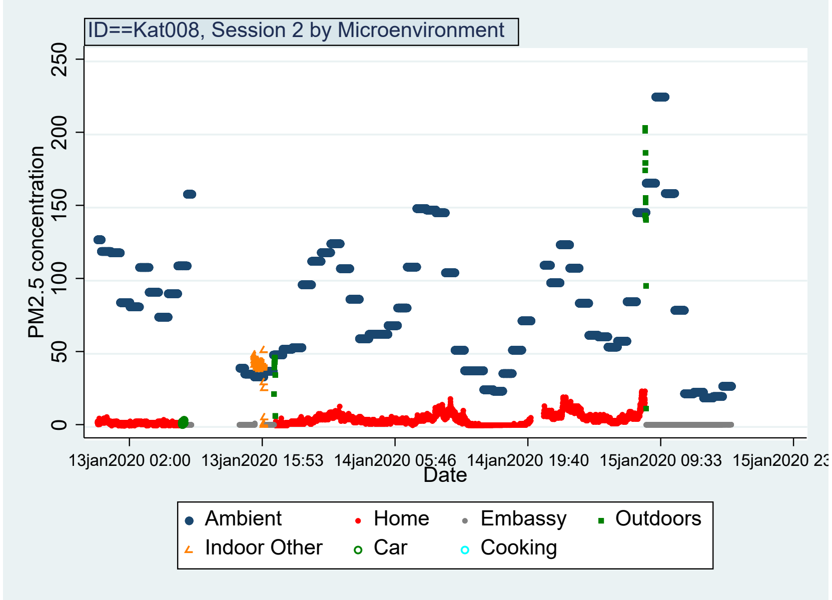


Kat 008

Worked at the US Embassy

- Session 1, started Nov 12, 2019
    - 10 room air cleaners at home, extra efforts to seal home (did not elaborate on specifics)
    - Duration = 39 hours
- Session 2, started Jan 13, 2020
    - 12 room air cleaners at home, extra efforts to seal home (did not elaborate on specifics)
    - Duration = 47 hours



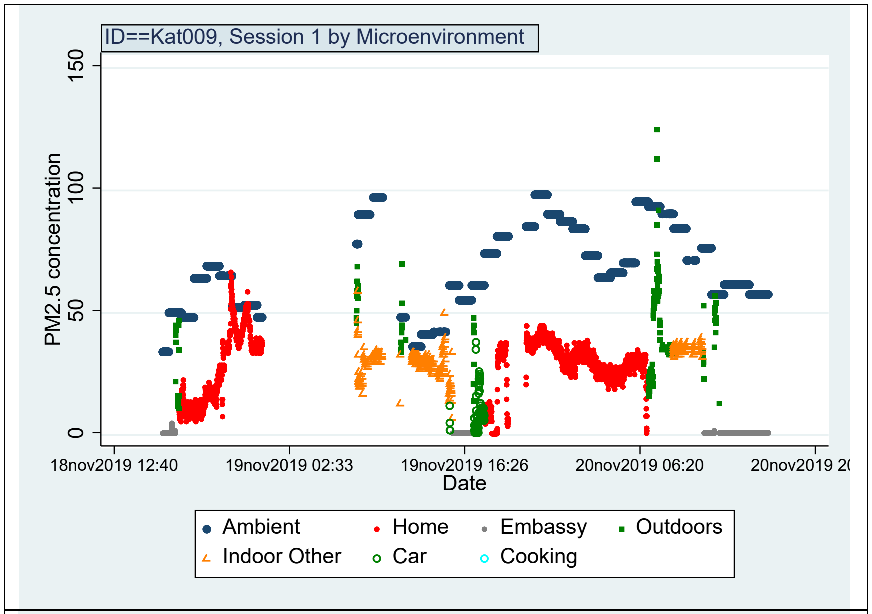


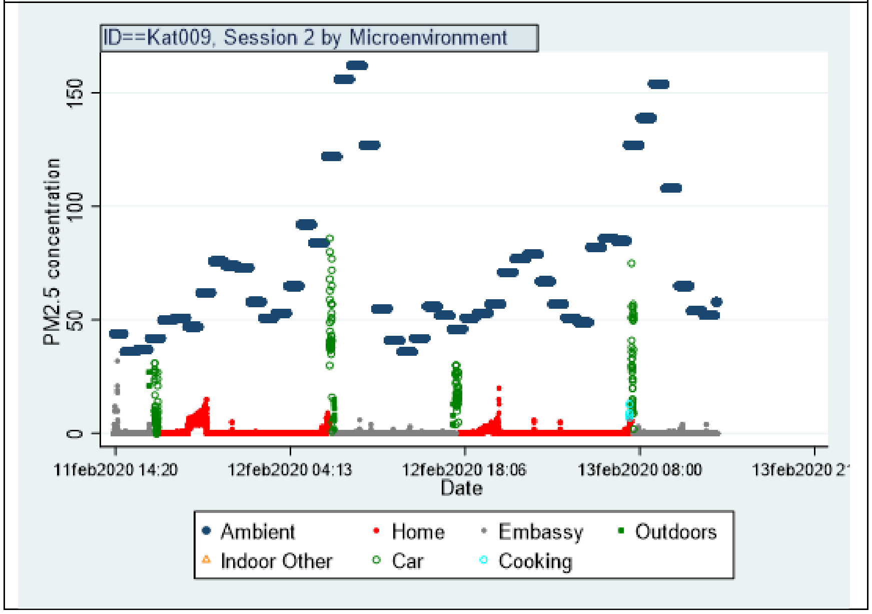
Kat 009

Worked at the US Embassy

Excluded from intervention study results due to missing data

- Session 1, started Nov 18 2019
    - 7 room air cleaners, sealed home – windows are taped, and some have plastic
    - Duration = 20 hours
- Session 2, started Feb 11, 2020
    - 9 room air cleaners, sealed home - windows are taped and some have plastic
    - Duration = 38 hours

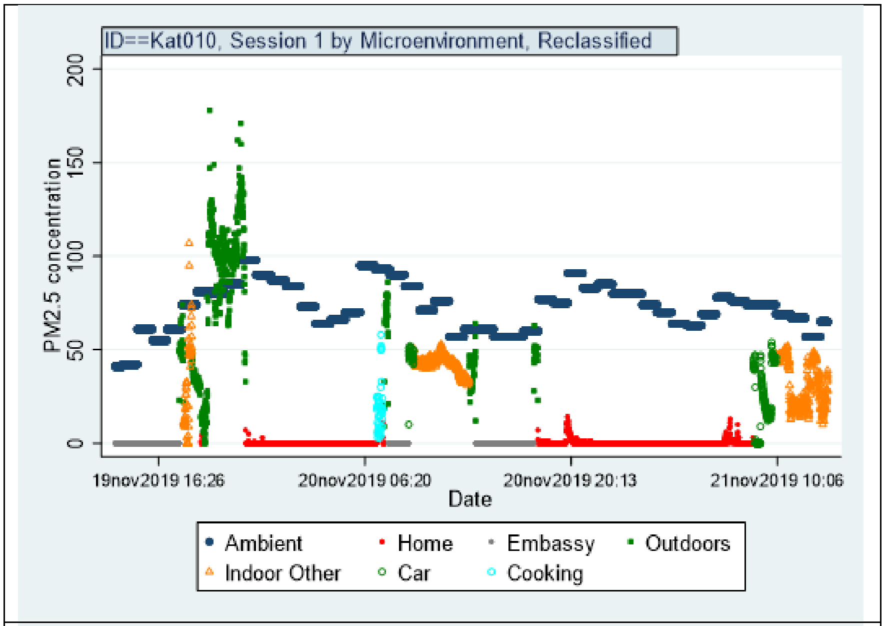


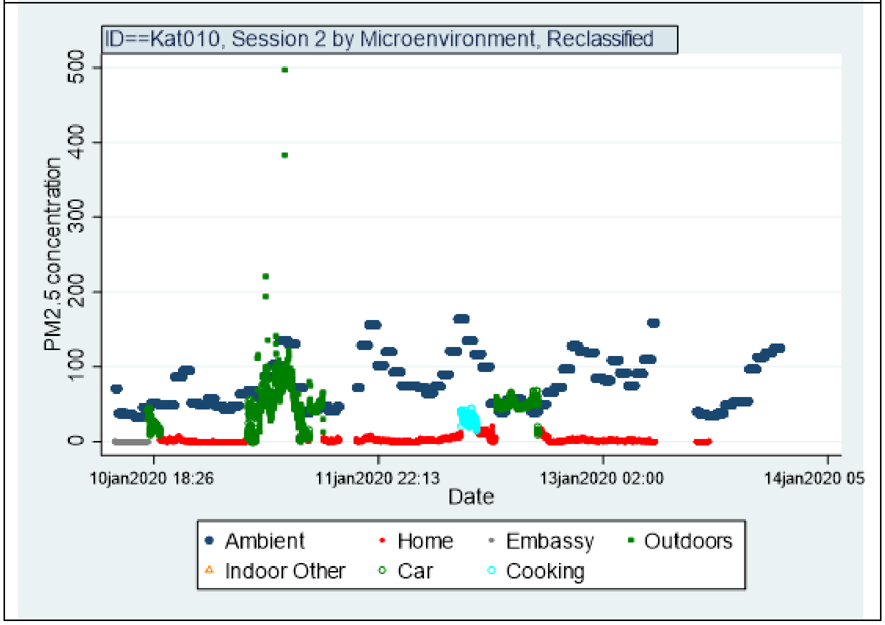


Kat 010

Worked at the US Embassy

- Session 1, started Nov 19 2019
  - 7 RACs at home, caulk, and weather tape on windows
  - Duration = 37 hours
- Session 2, started Feb 10 2020
  - 7 RACs at home, caulk, and weather tape on windows
  - Duration = 61 hours, 7 hours of missing data (1/11 602-1317)

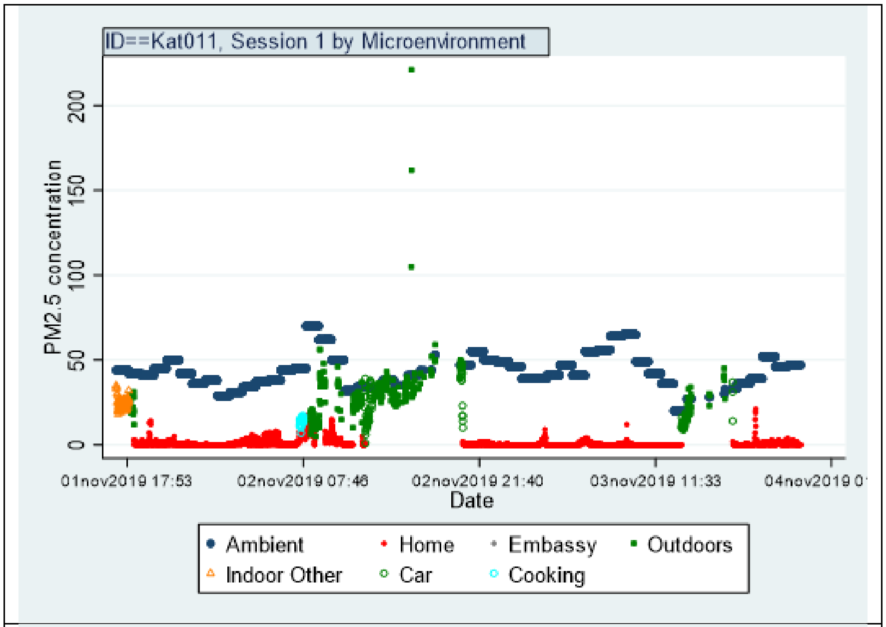


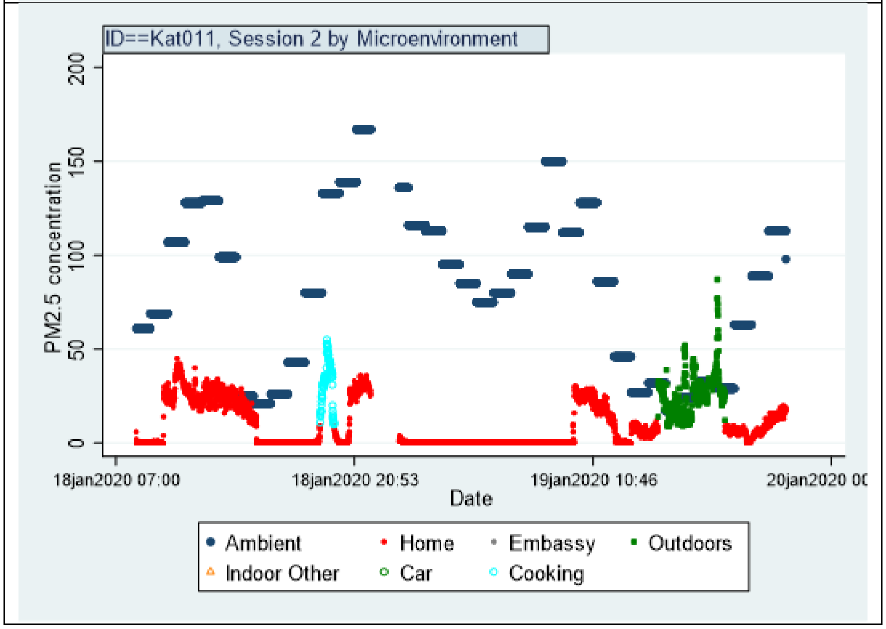


Kat 011

Worked at the US Embassy

- Session 1, started Nov 1 2019
    - 8 room air cleaners at home, home not sealed
    - Used Phora ambient data as the Embassy monitor was offline
    - Duration = 53 hours
- Session 2, started Jan 17 2020
    - 10 room air cleaners, sealed open areas with caulk
    - Painting in child’s bedroom on Jan 18 2020
    - Duration = 38 hours

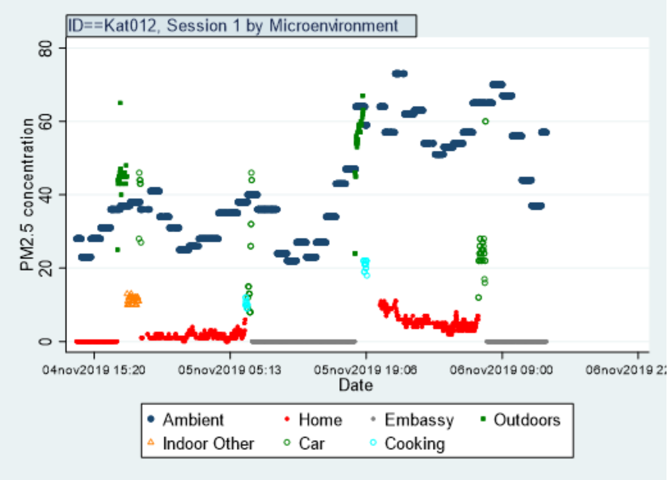


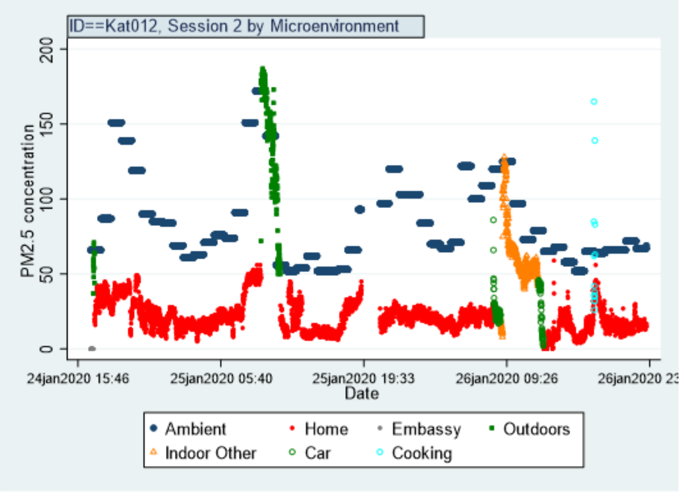


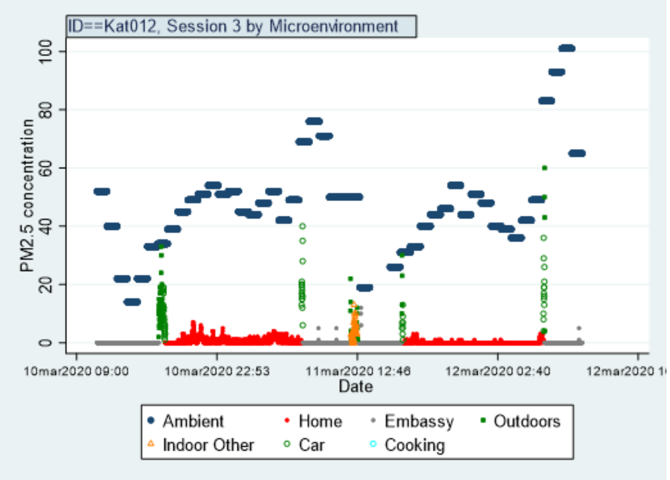
Kat 012

Worked at the US Embassy but also works off-site often

- Session 1, started Nov 14, 2019
    - 6 RACs at home, sealed windows in children's rooms
    - Duration= 41 hours
- Session 2, started Jan 24, 2020
    - Do not use this data in IO analysis - high home values between 10-50 unclear why based on log
    - Duration = 54 hours
- Session 3, started Mar 10, 2020
    - 8 RACs at home, sealed windows in children's rooms
    - Duration = 38 hours





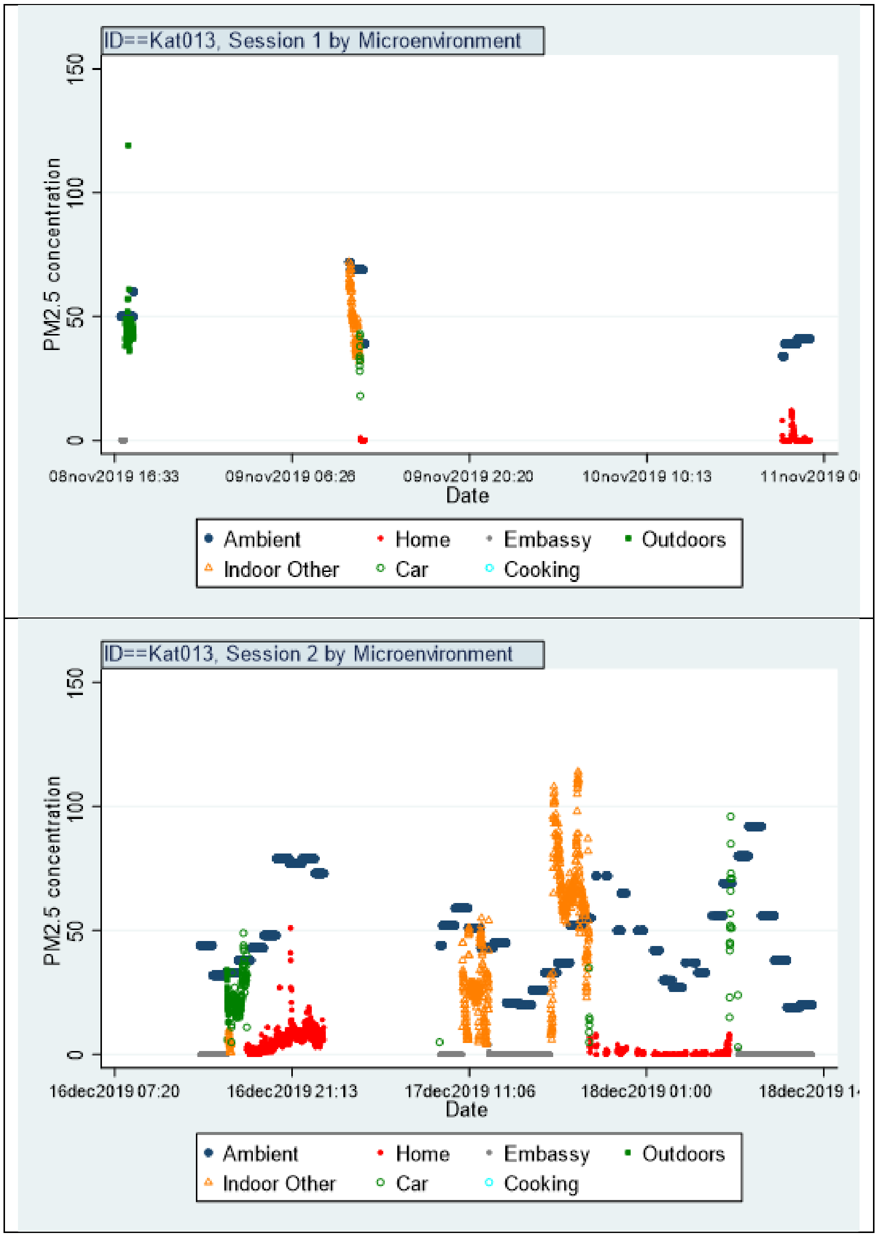


Kat 013

Eliminated from study due to missing data

Worked at the US Embassy

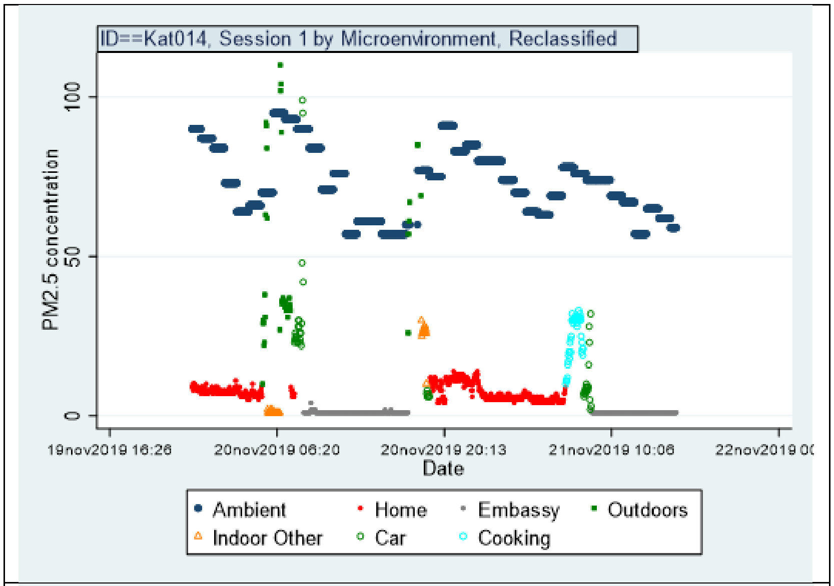
- Session 1, started 11/9/2019
  - 7 RACs at home, no efforts to seal home
  - Duration = 3 hours
- Session 2, started 12/16/2019
  - 9 RACs at home, no efforts to seal home
  - Duration = 17 hours

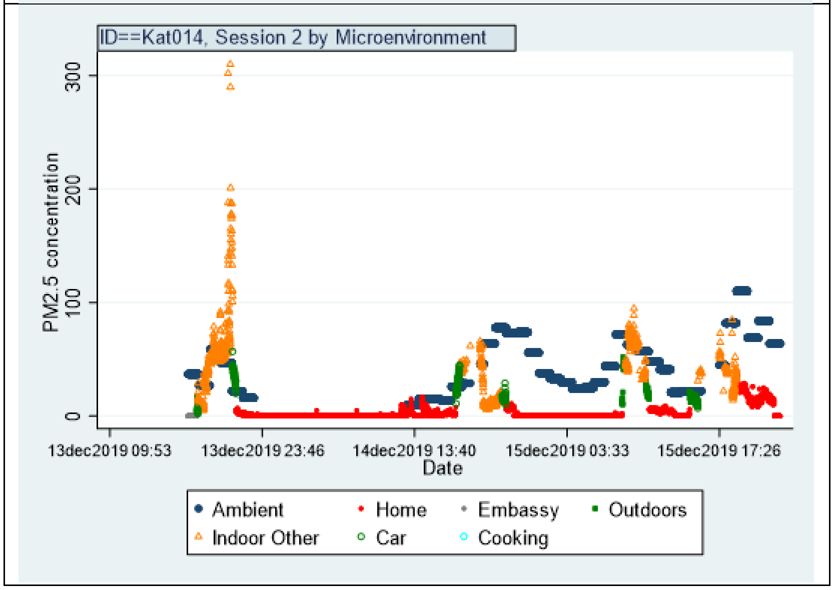


Kat 014

Worked at the US Embassy

- Session 1, Started Nov 19, 2019
  - 8 RACs at home, no efforts to seal home
  - Duration = 32 hours
- Session 2, Started Dec 13, 2019
  - 10 RACs at home, no efforts to seal home
  - Duration = 50 hours

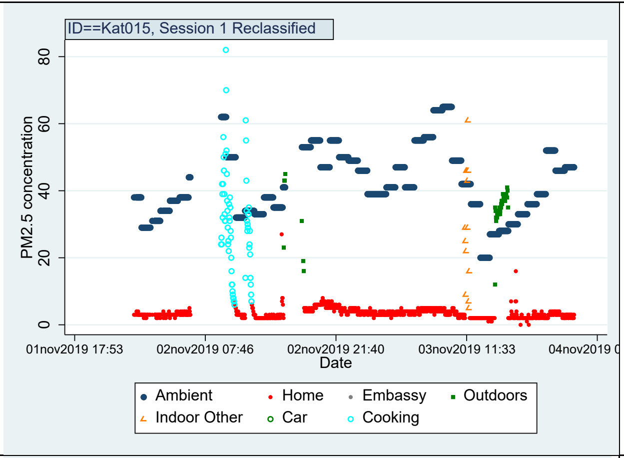


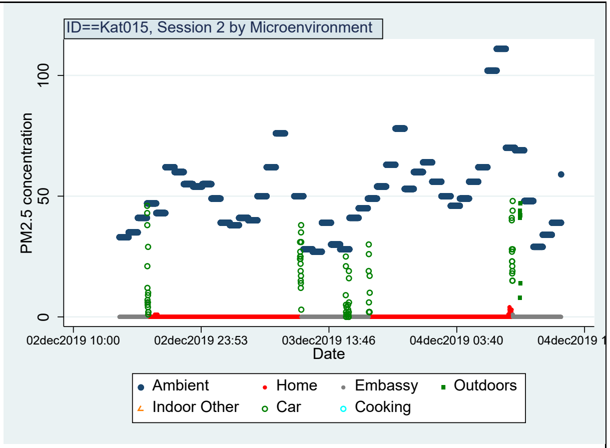


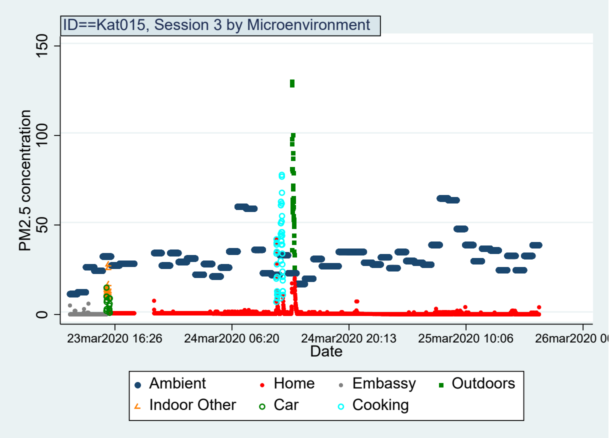
Kat 015

Worked at the US Embassy

- Session 1, started Nov 1, 2019
    - 7 room air cleaners at home, home sealed - plastic sheets on all first story windows inside or outside, extra door seal on front and back door weather stripping
    - Duration = 40 hours
- Session 2, started Dec 2, 2019
    - 9 room air cleaners at home, home sealed (no improvement from prior session)
    - Duration= 39 hours
- Session 3, started Mar 23, 2020
    - 9 room air cleaners at home, home sealed (no improvement from prior session)
    - Duration = 48 hours



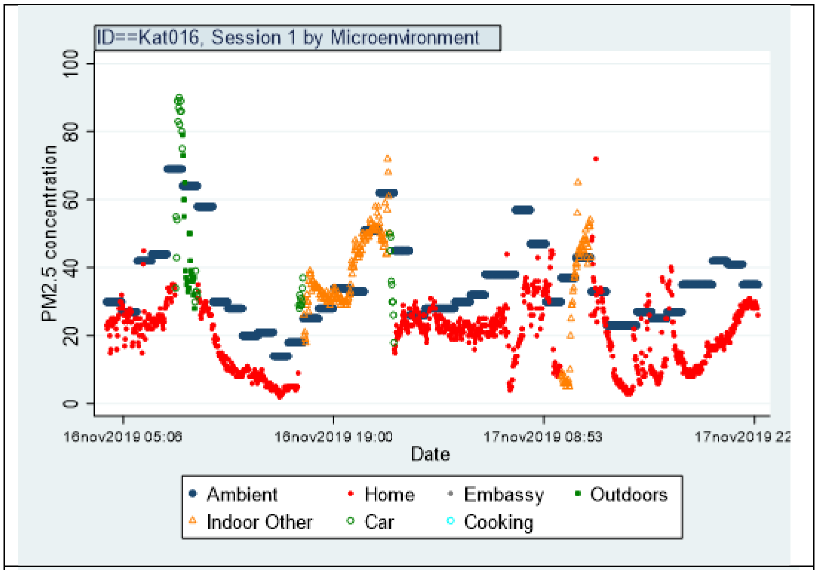


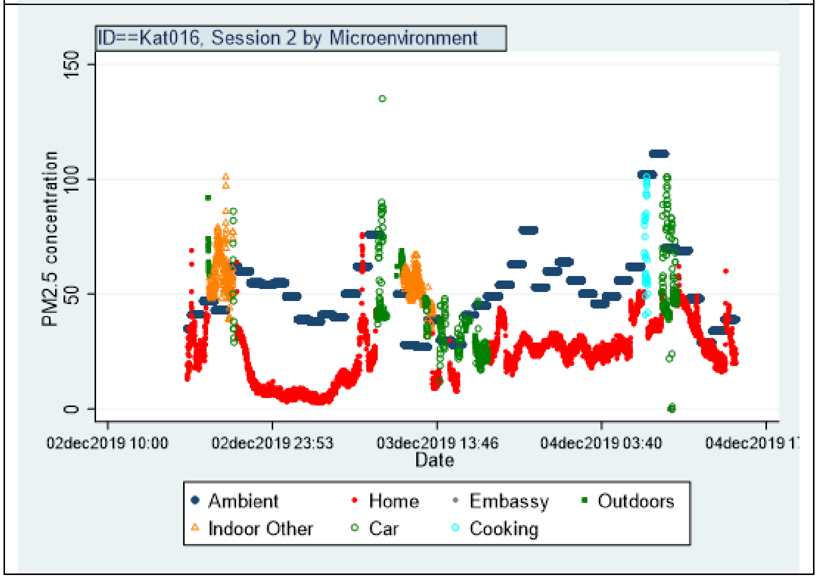


Kat 016

Did not work at the US Embassy

- Session 1, started Nov 17, 2019
    - 10 room air cleaners at home, home sealed – plastic used over bedroom windows
    - Note high PM Nov 16 overnight (~20) – why? Appears to be a very leaky home
    - Duration = 43 hours
- Session 2, started Dec 2, 2019
    - 10 room air cleaners at home, home sealed – plastic used over bedroom windows (no improvement from prior session)
    - Duration = 46 hours

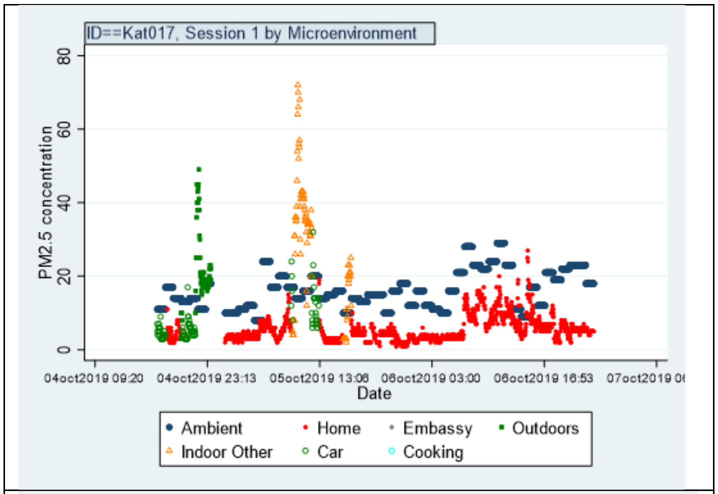


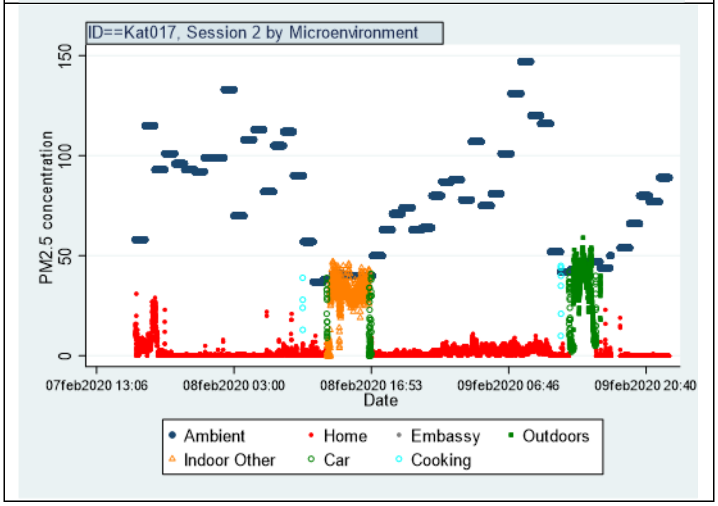


Kat 017

Did not work at the US Embassy

- Session 1, started Oct 4, 2019
  - 10 room air cleaners at home, home was not sealed
  - Duration = 47 hours
- Session 2, started Feb 7, 2020
  - 12 room air cleaners at home, home sealed – used caulk and door snakes
  - Duration = 54 hours

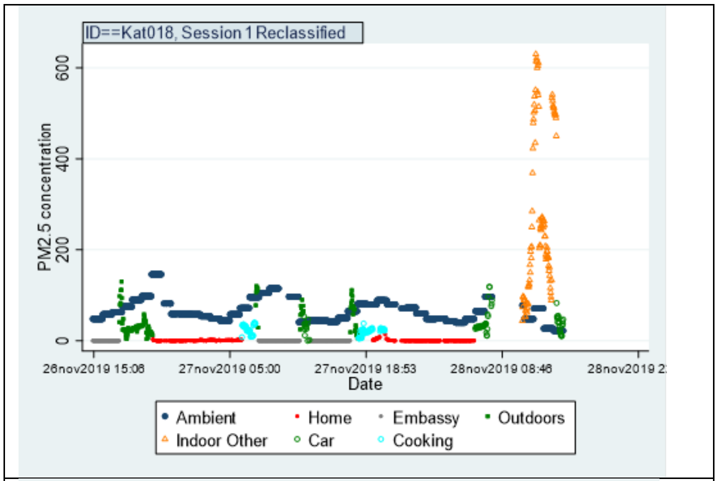


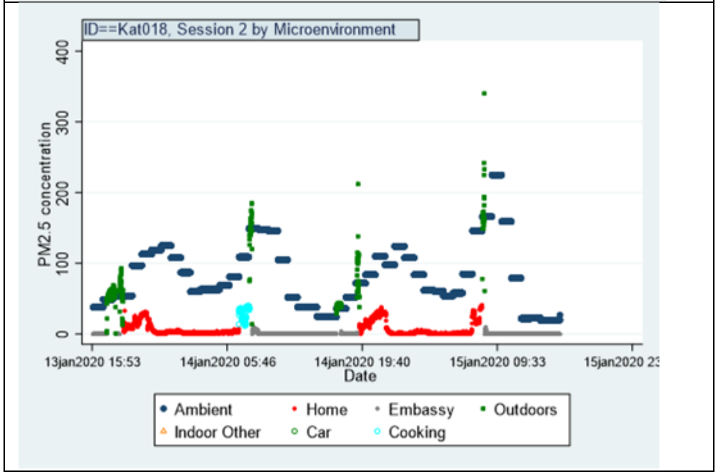


Kat 018

Worked at the US Embassy

- Session 1, started Nov 26, 2019
  - 4 RACs at home, no efforts to seal home and likes to keep windows open
  - Duration = 36 hours
- Session 2, started Jan 13, 2020 this is a “pre” session
  - 4 RACs at home, no efforts to seal home and likes to keep windows open
    - some home peaks that correlate with outdoor peaks
  - Duration = 37 hours
- Session 3, started Mar 23, 2020
  - 6 RACs at home, no efforts to seal home and likes to keep windows open
  - High home values possibly due to opening a window (it is March, nice weather)
  - Duration = 45 hours

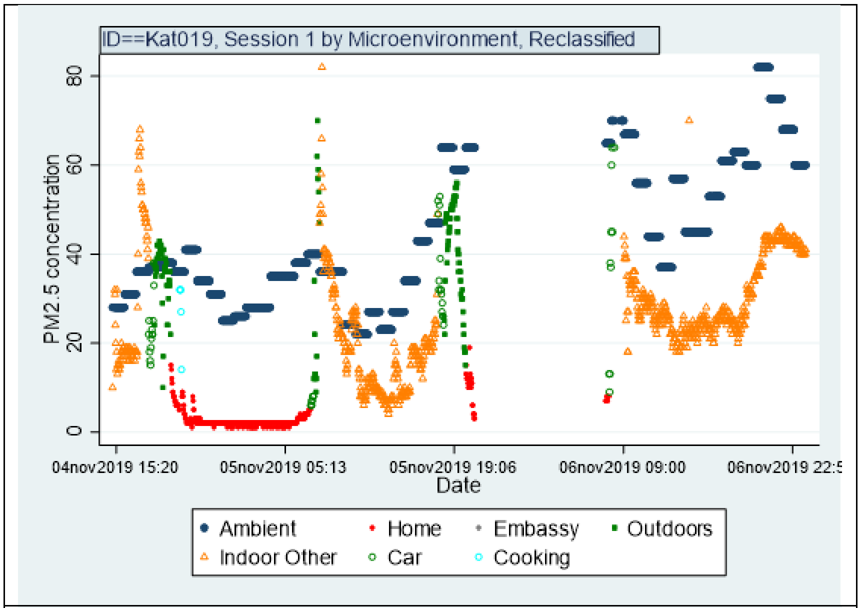


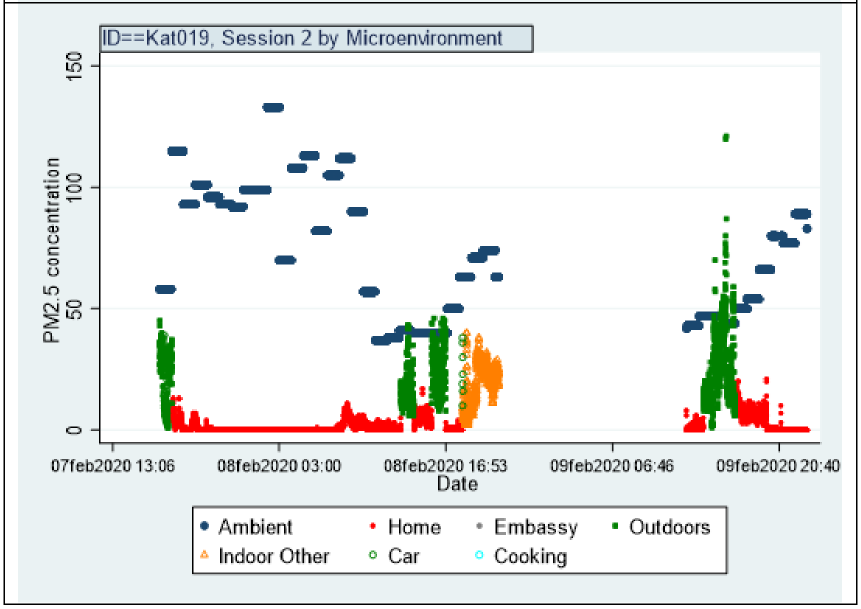


Kat 019

Did not work at the US Embassy, worked in the Peace Corps building

- Session 1, started Nov 4, 2019
    - 3 RACs at home and reported only using room air cleaners “sometimes” in living room, no efforts to seal home
    - Duration = 39 hours
    - very detailed time activity log
- Session 2, started Feb 7, 2020
    - 5 RACs at home, no efforts to seal home
    - Duration = 38 hours

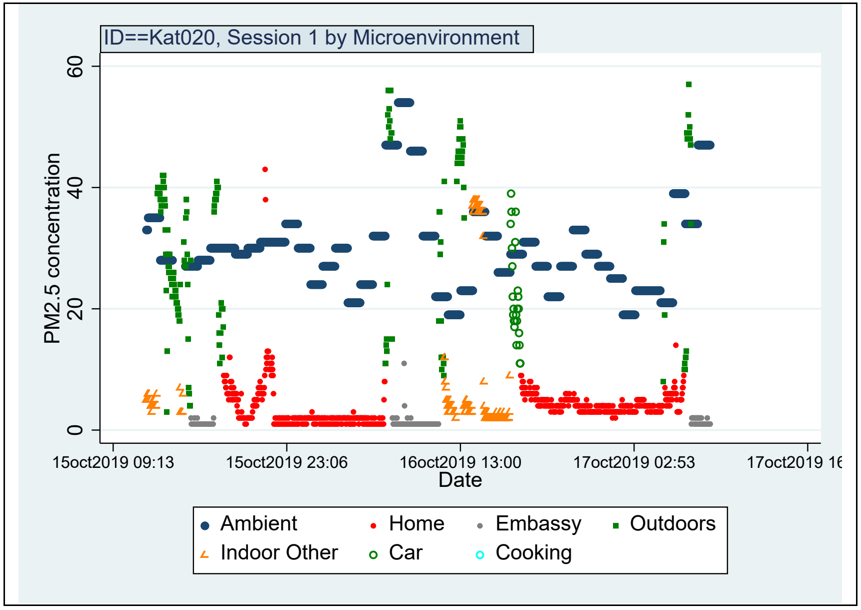




Kat 020

Worked part time at the US Embassy

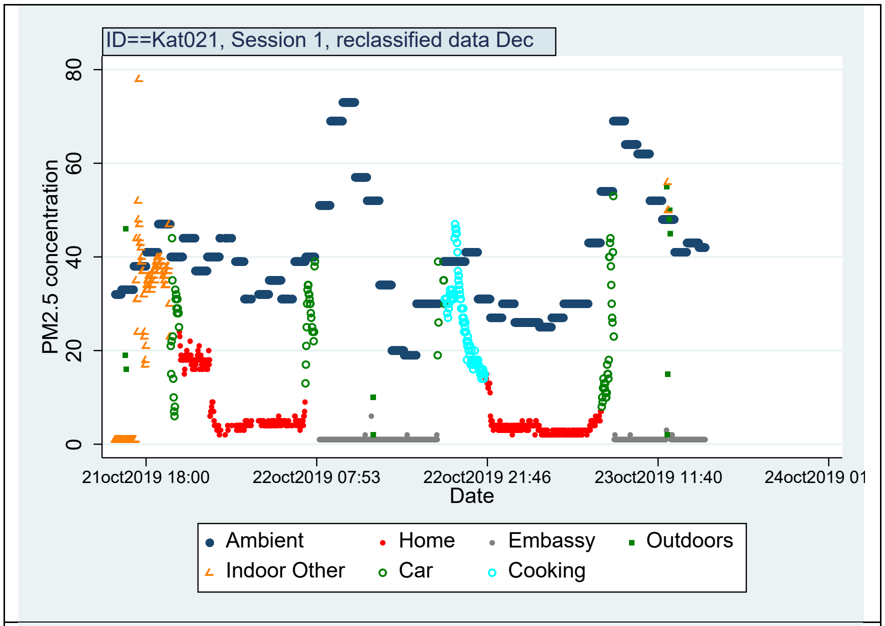
- Session 1, started Oct 15 2019
    - 9 room air cleaners at home, no efforts to seal home and participant noted that house has exhaust fans with large spaces opening to the outdoors
    - Duration = 37 hours
- Session 2, started Feb 7 2020
    - 11 room air cleaners at home, home sealed – tape on first floor windows and foam on doors
    - Unfortunately, data did not load to server for this session

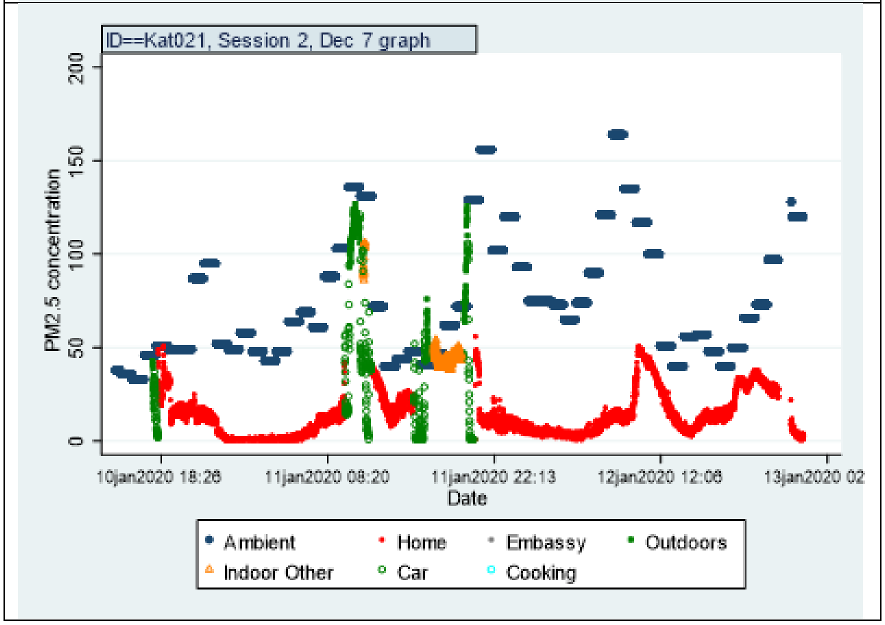


Kat 021

Worked at US Embassy

- Session 1
  - 2 RACs at home, no extra efforts to seal home
  - May have kept windows open on Oct 21 before going to sleep (clear drop off by 2300 and warmer temp on monitor), Oct 5 2022-2042 reclass to cooking based on time of day
  - Duration = 36 hours
- Session 2
  - 4 RACs at home, no extra efforts to seal home
  - Note – variation in home PM makes me think the home is very leaky
  - Duration = 54 hours

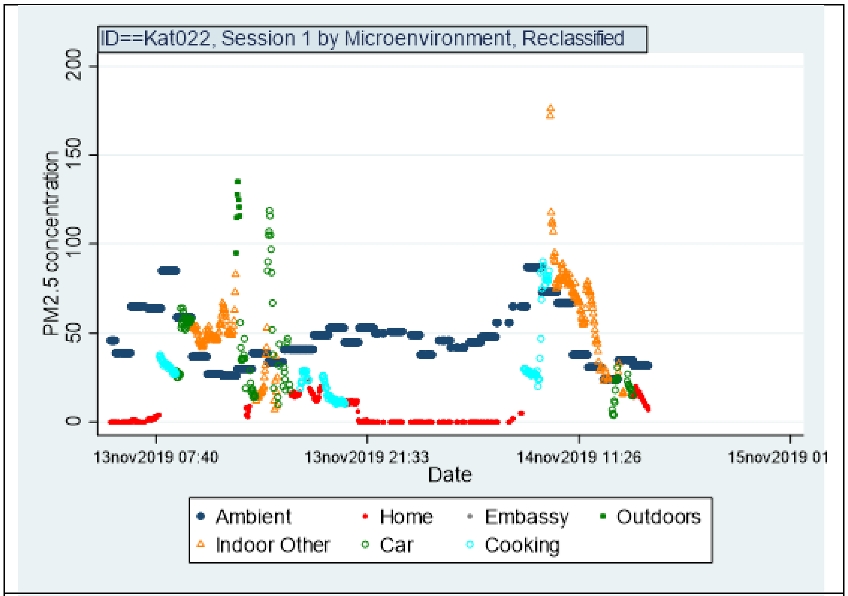


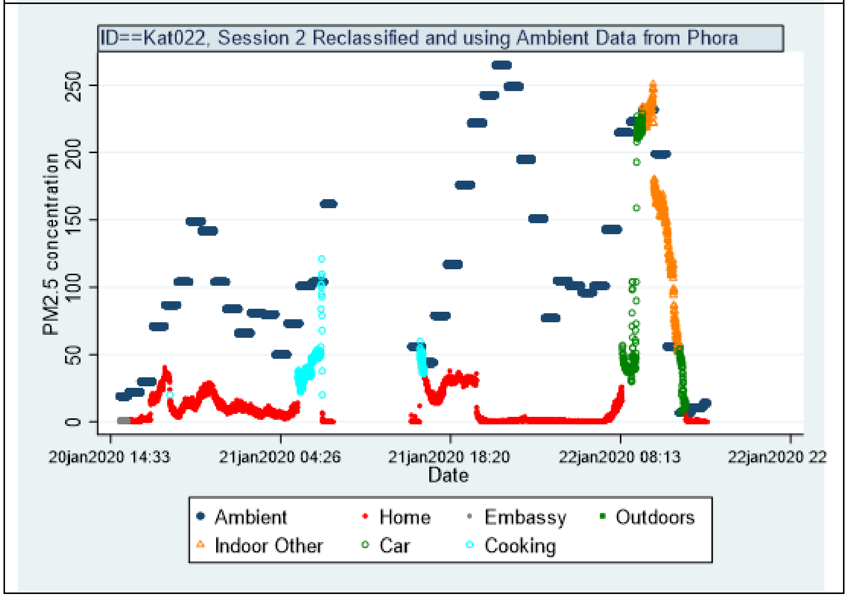


Kat 022

Did not work at the US Embassy (unemployed spouse)

- Session 1, started Nov 12 2019
  - 5 RACs at home, no efforts to seal home
  - Duration = 24 hours
- Session 2, started Jan 21 2020
  - 7 RACs at home and reports using room air cleaners in living room “sometimes”, no efforts to seal home
  - Duration = 41 hours

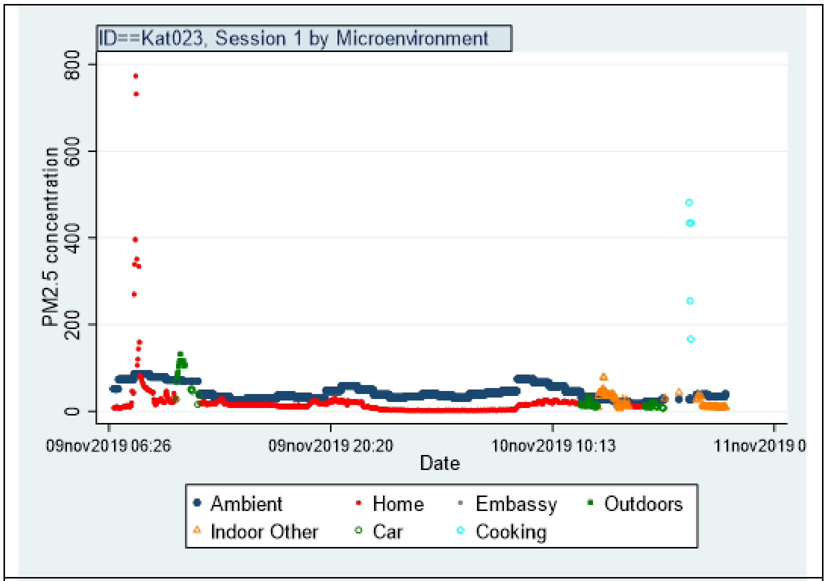


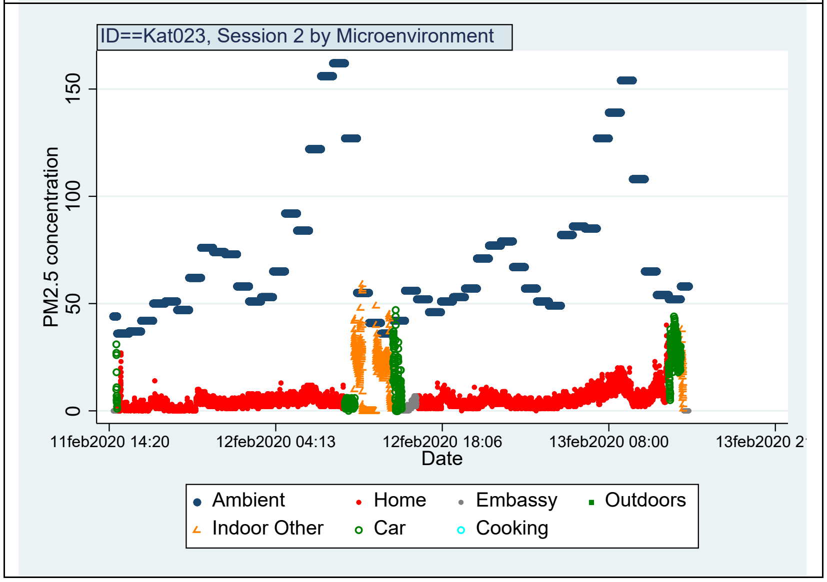


Kat 023

Did not work at US Embassy

- Session 1, started Nov 8, 2019
  - 6 room air cleaners at home, no efforts to seal home
  - Duration = 30 hours
  - Check for an updated graph without the early red peak
- Session 2, started Feb 11, 2020
  - 7 room air cleaners at home, no efforts to seal home
  - Duration = 46 hours

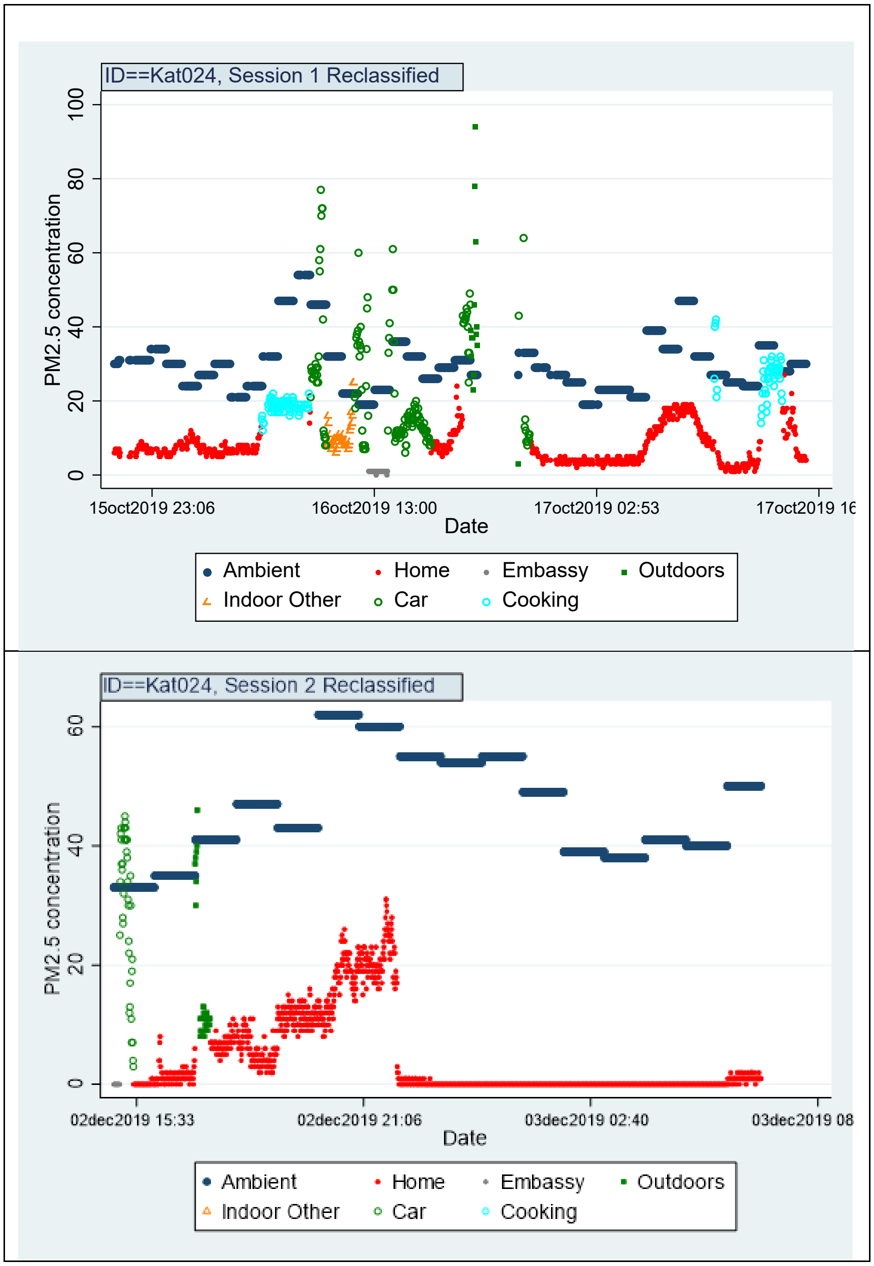




Kat 024

Did not work at the US Embassy

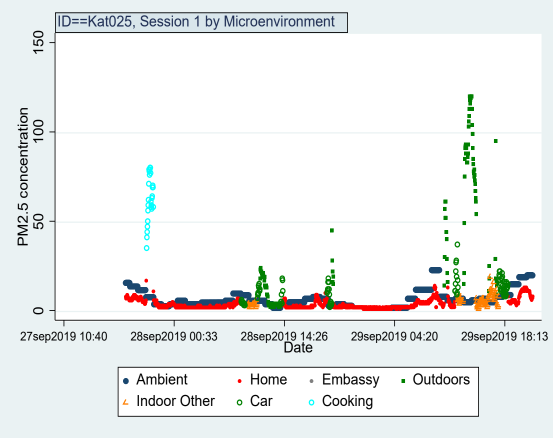
- Session 1, started Oct 15 2019
    - 7 RACs at home, no efforts to seal home
    - Duration = 40 hours
- Session 2, started Dec 4 2019
    - 9 RACs at home, sealed windows with plastic

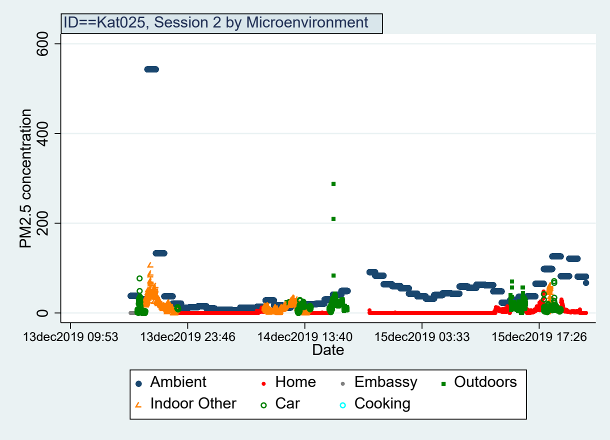


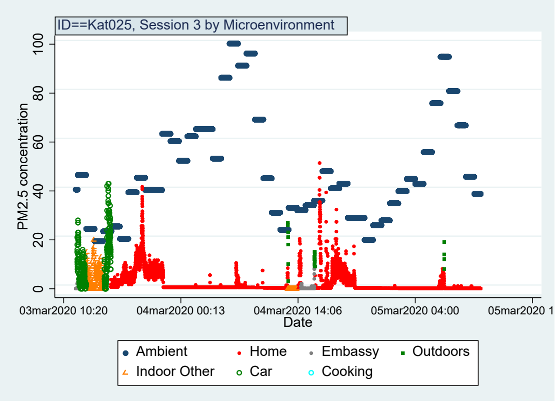
Kat 025

Did not work at the US Embassy

- Session 1, started Sep 11, 2019
    - 8 room air cleaners, no efforts to seal home
    - Duration = 51 hours
- Session 2, started Dec 13, 2019
    - 10 room air cleaners, used weather stripping to seal home
    - Used Phora data as Embassy monitor was down
    - Duration = 42 hours
- Session 3, started Mar 3, 2020
    - 10 room air cleaners, used weather stripping on doors, windows were refitted to not have gaps
    - Duration = 44 hours



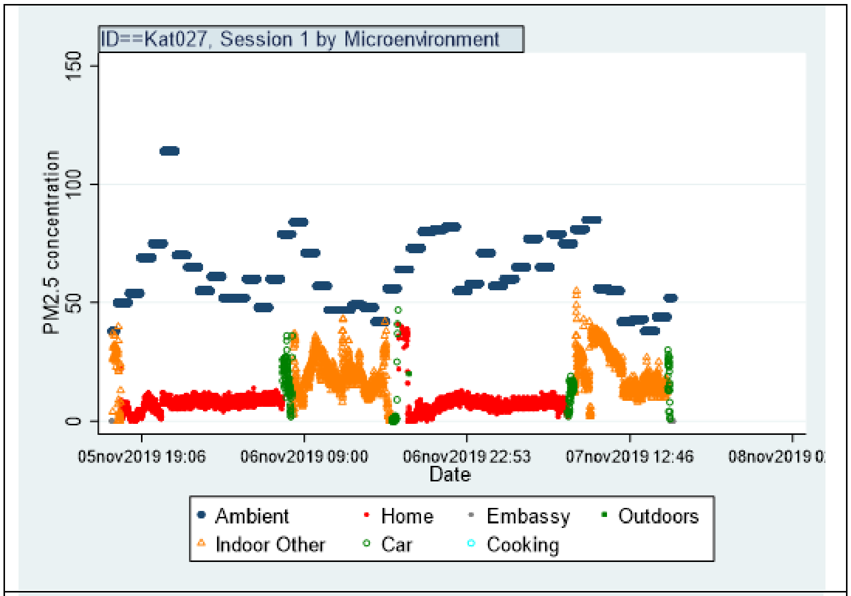


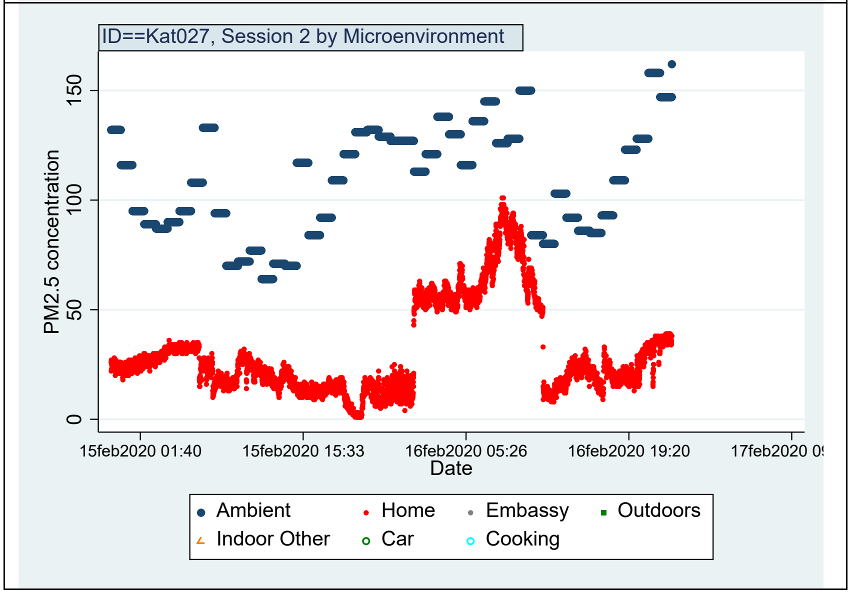


Kat 027

Did not work at the US Embassy

- Session 1, started Nov 5, 2019
  - 11 room air cleaners, used extra efforts to seal home but respondent did not describe what they did
  - Duration = 38 hours
- Session 2, started Feb 14, 2020
  - 11 room air cleaners, same extra efforts to seal home were in place but not described
  - Duration = 48 hours



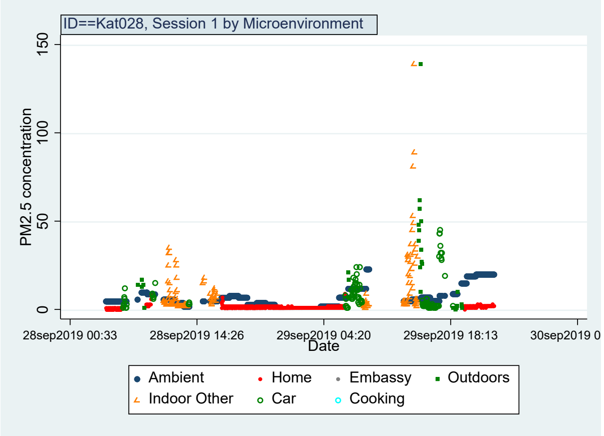


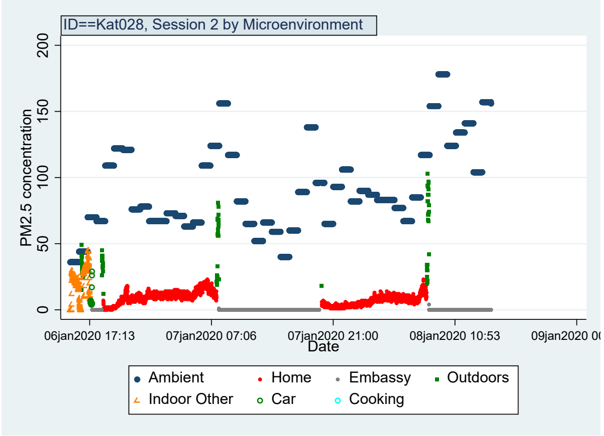
Kat 028

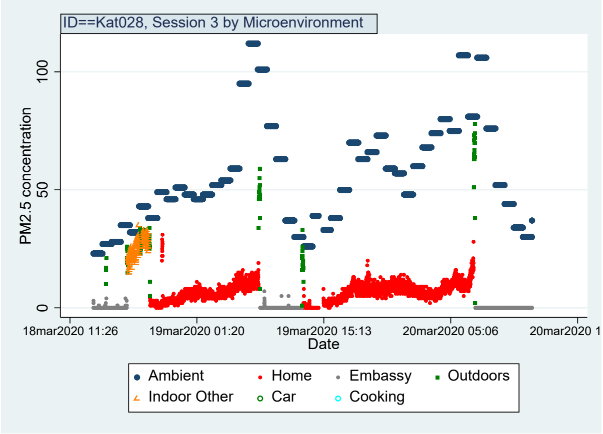
Worked at the US Embassy

Compared session 1 to 3 in intervention study

- Session 1, started Sep 28 2019
    - 4 room air cleaners, no efforts to seal home
    - Duration = 36 hours
    - Ambient data a bit hard to see here as personal PM2.5 was so low except for a few occasions
- Session 2, started Jan 6, 2020 this is a pre session
    - 4 room air cleaners, doors had seals installed at the base in order to limit air entry
    - Duration = 25 hours
- Session 3, started Mar 18, 2020
    - 6 room air cleaners, doors had seals installed at the base in order to limit air entry (same as Session 2)
    - Duration = 36 hours





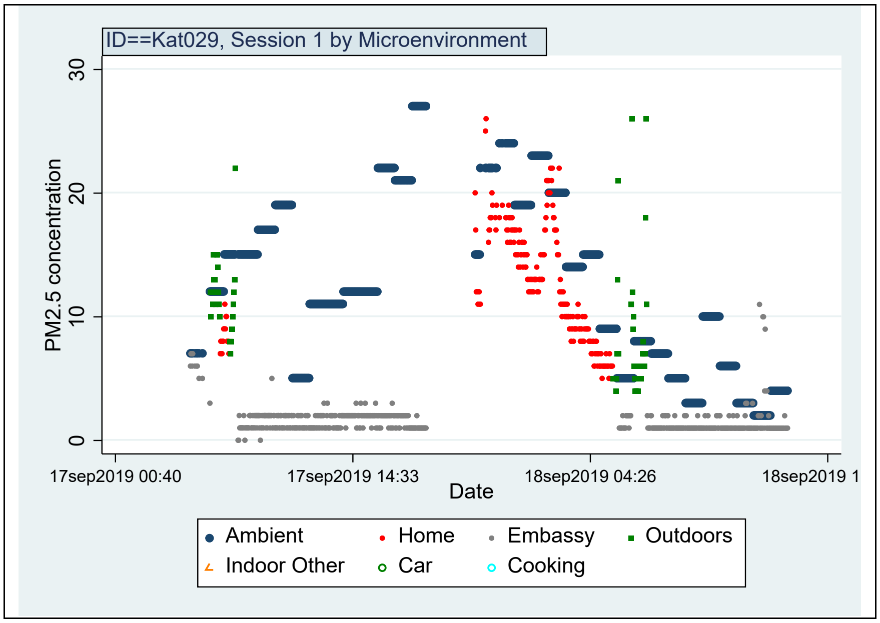


Kat 029

Worked at US Embassy

Excluded from study as only had 1 monitoring session

- Session 1, started Sep 17, 2019
  - 6 room air cleaners, no efforts to seal home
  - Duration = 23 hours

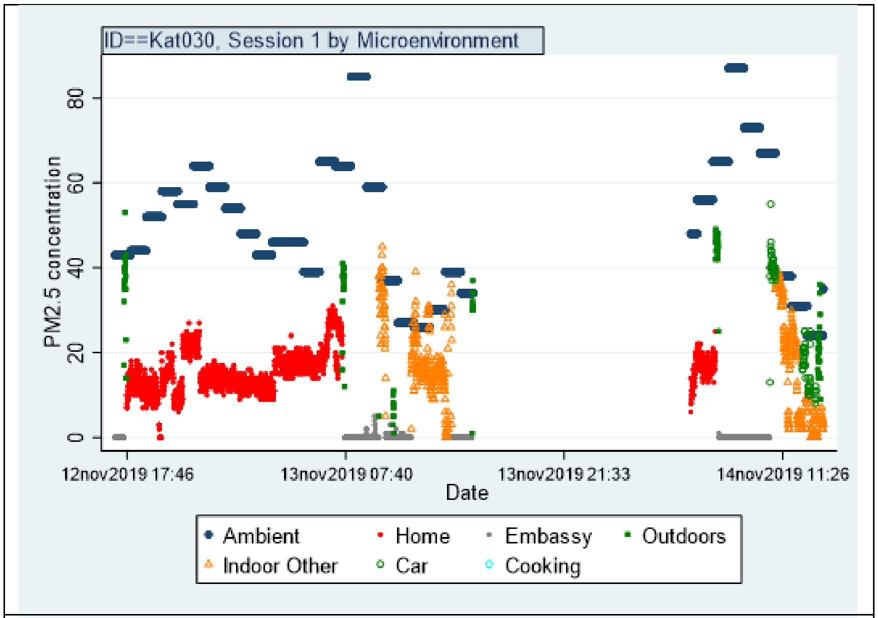


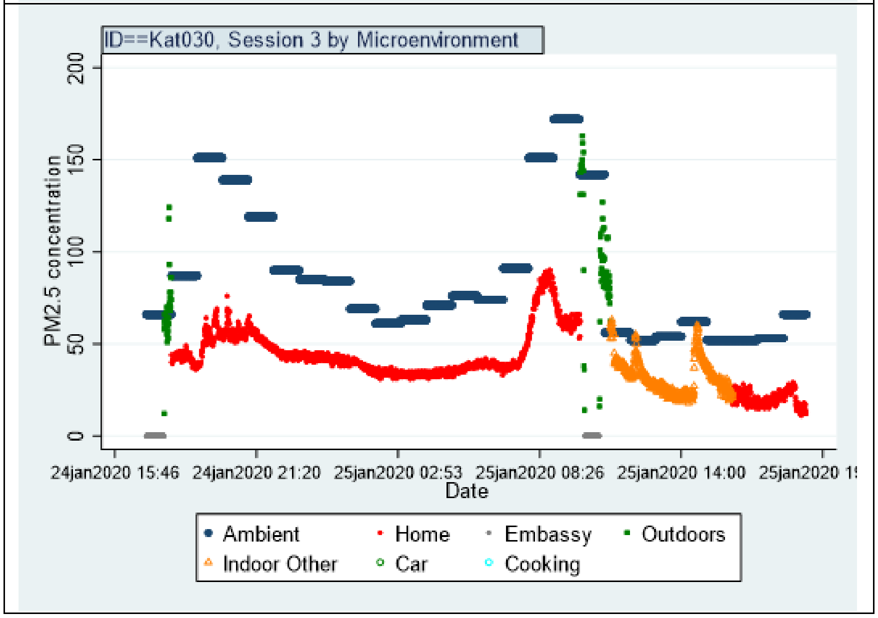
Kat 030

Worked at US Embassy

Compare Session 1 to Session 3

- Session 1, started Nov 12, 2019
  - 5 room air cleaners, no efforts to seal home
  - Duration = 15 hours
- Session 2, no data recorded
- Session 3, started Jan 24, 2020
  - 7 room air cleaners, sealed home
  - Duration 25 hours

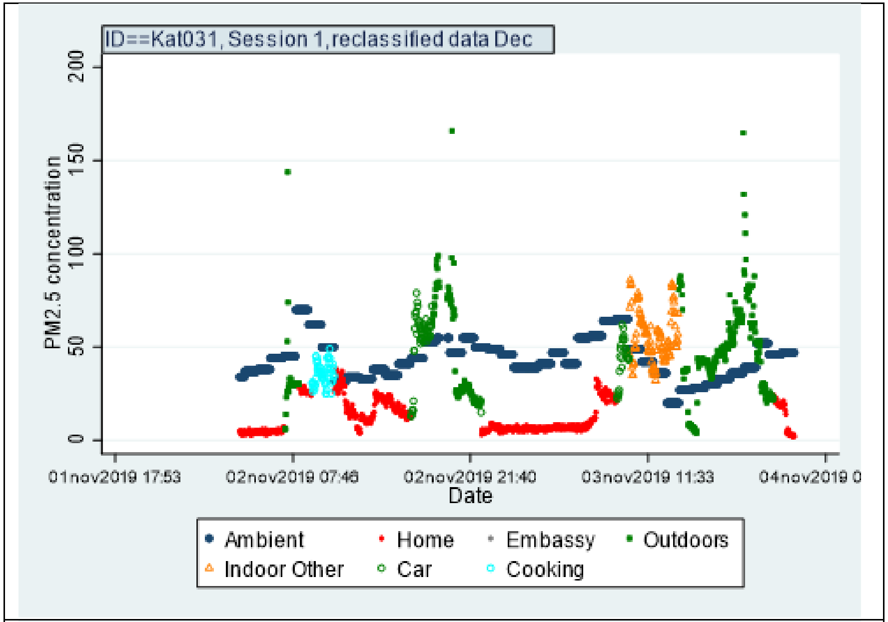


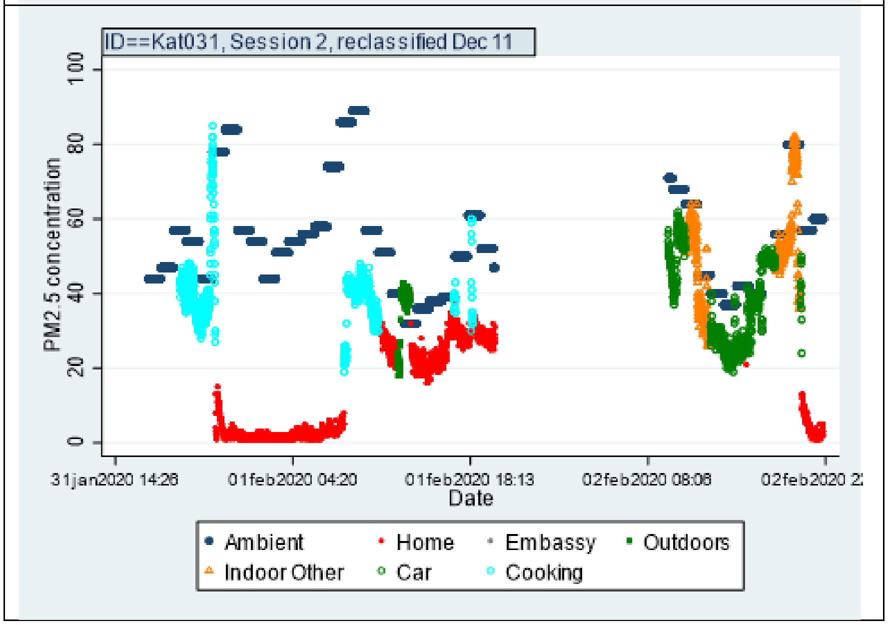


Kat 031

Did not work at the US Embassy

- Session 1, started Nov 2, 2019
  - 8 room air cleaners, no efforts to seal home
  - 43 hours duration
- Session 2, started Jan 3, 2020
  - 10 room air cleaners, no efforts to seal home
  - 38 hours duration (approx. 10 hours missing data)





Appendix 4: Supplementary material: Health impacts of changing exposure to $PM_{2.5}$ for diplomats with multiple international relocations: modeling study

Supplementary Materials

Health impacts of changing exposure to $PM_{2.5}$ for diplomats with multiple international relocations: modeling study

Leslie Edwards[a]*, James Milner[a], Ai Milojevic[a]

[a]London School of Hygiene and Tropical Medicine, London, England, United Kingdom

*Corresponding Author: Leslie.Edwards@lshtm.ac.uk

Table of Contents

The following figures are included as an appendix to this thesis and were not previously published in conjunction with the research article

Figure A.26: Assignment 9, older diplomat in “Very high 20 years” assignment; lagged risk relative (RR) of mortality

Figure A.27: Assignment 9, young diplomat in “Very high 20 years” assignment; lagged risk relative (RR) of mortality

Figure A28: Assignment 9, child of a diplomat in “Very high 20 years” assignment; lagged risk relative (RR) of mortality

Figure A.29: Assignment 10, older diplomat in “Standard A with mitigation” assignment; lagged risk relative (RR) of mortality

Figure A30: Assignment 10, young diplomat in “Standard A with mitigation” assignment; lagged risk relative (RR) of mortality

Figure A.31: Assignment 10, child of a diplomat in “Standard A with mitigation” assignment; lagged risk relative (RR) of mortality

Table A.1: Ten diplomatic assignments with the city and number of years in each city indicated[1].

Assignment	Assignment Description	Assignment locations (number of years in each location)
1	**Standard A**	Manila (2 years), Riyadh (2), Munich (2), San Francisco (3), Kathmandu (2), Bangkok (3), Washington, DC (2), Dakar (2), Washington, DC (1)
2	**Standard B**	Yaoundé (2), Tirana (2), Amman (3), Dhaka (3), Washington, DC (5), Hanoi (3), Stockholm (2)
3	**Standard A x 2[1]**	Manila (2 years), Riyadh (2), Munich (2), San Francisco (3), Kathmandu (2), Bangkok (3), Washington, DC (2), Dakar (2), Washington, DC (1), Manila (2), Riyadh (2), Munich (2), San Francisco (3), Kathmandu (2), Bangkok (3), Washington, DC (2), Dakar (2), Washington, DC (1)
4	**High 1 year & low 3 years cycle**	Riyadh (1), Washington, DC (3), Kathmandu (1), Washington, DC (3), Yaoundé (1), Washington, DC (3), Dakar (1), Washington, DC (3), Riyadh (1), Washington, DC (3)
5	**High 2 years & low 2 years cycle**	Riyadh (2), Washington, DC (2), Kathmandu (2), Washington, DC (2), Yaoundé (2), Washington, DC (2), Dakar (2), Washington, DC (2), Riyadh (2), Washington, DC (2)
6	**High 3 years & low 1 year cycle**	Riyadh (3), Washington, DC (1), Kathmandu (3), Washington, DC (1), Yaoundé (3), Washington, DC (1), Dakar (3), Washington, DC (1), Riyadh (3), Washington, DC (1)
7	**High 4 years x 5**	Riyadh (4), Kathmandu (4), Yaoundé (4), Dakar (4), Riyadh (4)
8	**Very high 2 years & low 2 years cycle**	New Delhi (2), Washington, DC (2), New Delhi (2), Washington, DC (2), New Delhi (2), Washington, DC (2), New Delhi (2), Washington, DC (2), New Delhi (2), Washington, DC (2)
9	**Very high 20 years**	New Delhi (20)
10	**Standard A with mitigation[2]**	Manila* (2 years), Riyadh* (2), Munich (2), San Francisco (3), Kathmandu* (2), Bangkok* (3), Washington, DC (2), Dakar* (2), Washington, DC (1)

[1] Each of the assignments have a 20 year duration except for profile 3 which had a 40 year duration.

[2] Air purifiers provided to diplomats for use in their residence while working in cities in Africa and Asia. Cities where air purifiers were provided are indicated with an asterisk (*).

Table A.2: Example calculations of the adjusted mortality rate for COPD using an inception lag and a cessation lag

Inception lag

In 2000, a person moved from Washington, DC to Manila, Philippines. In 1999, Washington, DC's annual $PM_{2.5}$ mean was 13.2 $\mu g/m^3$ and the GBD C-R function (reported as relative risk (RR)) of COPD mortality was 1.09. In 2000, Manila's annual $PM_{2.5}$ mean was 19.0 $\mu g/m^3$ and the GBD C-R function RR of COPD mortality was 1.15. To calculate the adjusted RR of COPD mortality in 2000, the 1st year in Manila:

1. Lag the risk for Manila first by dividing the Manila RR by the Washington, DC RR and identify the excess risk due to Manila by subtracting 1
    - (1.15/1.09) - 1 = 0.05
2. Apply a 20-year inception lag to 0.05, the first year of lag is 30% of the lagged risk
    - (0.05 * 0.30) +1 = 1.02
3. Multiply the RR for Washington, DC (1.09) by the lagged risk for Manila RR/Washington, DC RR (this is 1.02 as indicated in step 2)
    - Adjusted RR in the first year in Manila = 1.09 * 1.02 = 1.11
5. Continue this calculation for 20 years each year up to 20 years in Manila or until the diplomat moves to an area with a change in $PM_{2.5}$.

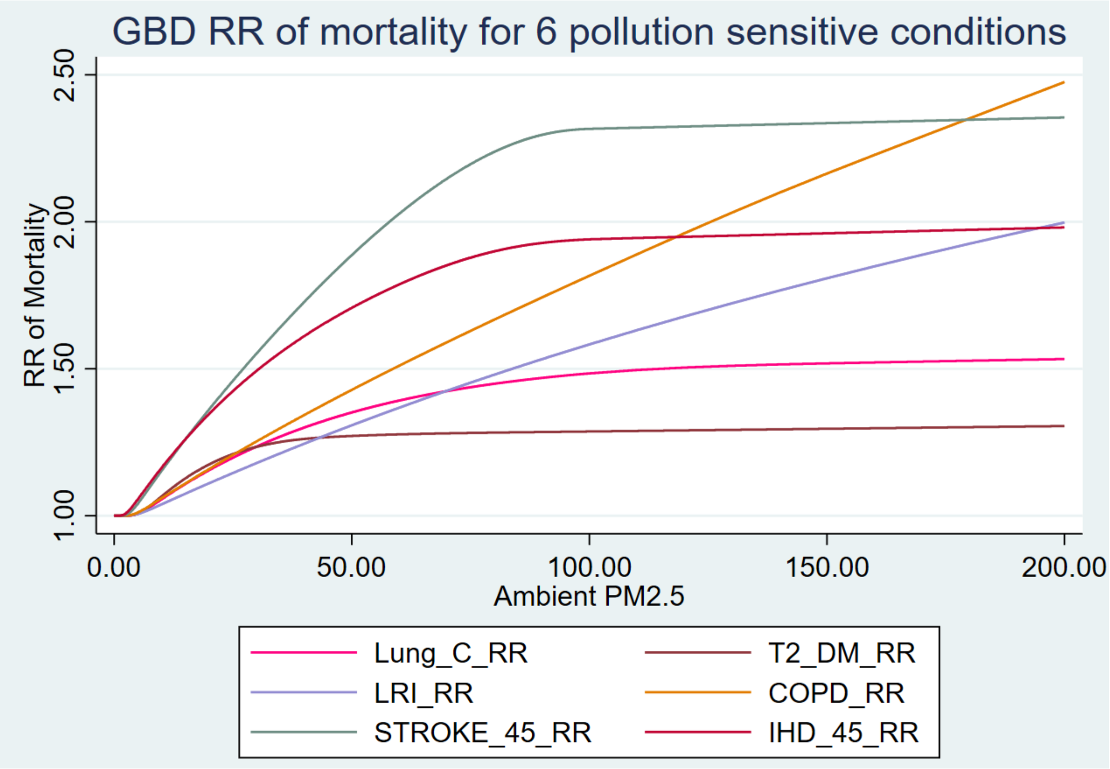
Cessation lag

In 2004, a person has lived in Riyadh, Saudi Arabia for 2 years and is moving to Munich, Germany. In 2003, Riyadh's annual $PM_{2.5}$ mean was 50 $\mu g/m^3$ and the GBD C-R function of COPD mortality for this $PM_{2.5}$ level was 1.43. In 2004, Munich's annual $PM_{2.5}$ mean was 18.5 $\mu g/m^3$ and the GBD C-R function of COPD mortality for this $PM_{2.5}$ level was 1.43. To calculate the adjusted RR of COPD mortality for 2004, the 1st year in Munich:

1. Because the person had only lived in Riyadh for 2 years and had moved there from a city with much lower ambient $PM_{2.5}$, the person's evolved RR of COPD mortality was 1.25 and not the full RR for Riyadh, 1.43
2. Lag the continued risk for Riyadh by dividing the evolved Riyadh RR divided by the Munich RR and identify the excess risk due to Riyadh by subtracting 1
    - (1.25/1.14) - 1 = 0.09
3. Apply a 20-year cessation lag to 0.09, the first year of the cessation lag is 70% of the lagged risk
    - (0.09 * 0.70) + 1 = 1.07
4. Multiply the RR for Munich (1.14) by the lagged risk for evolved Riyadh RR/Munich RR (1.07)
    - 1.14 * 1.07 = 1.22
5. Continue this calculation for the remaining 19 years, unless the person moves again

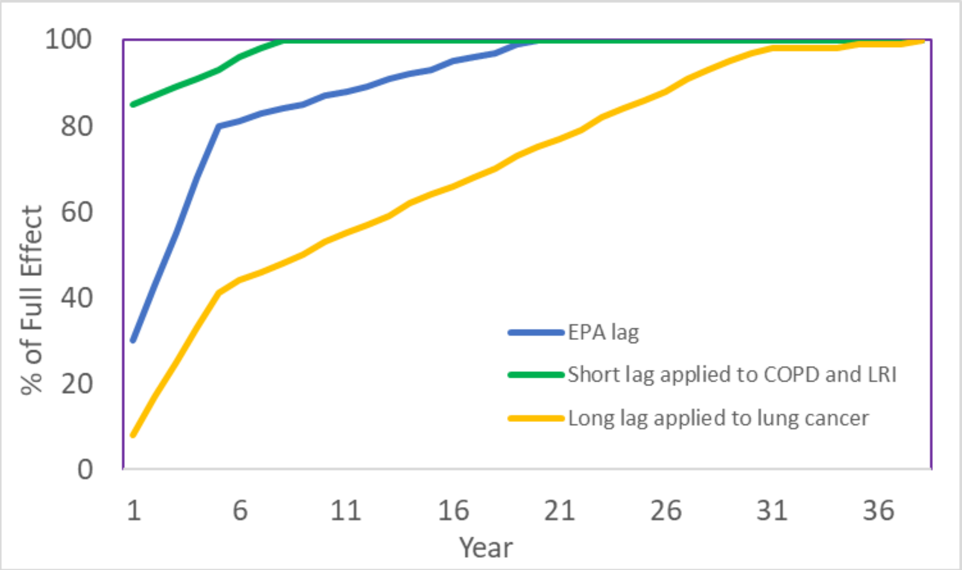
Table A.3: Assumptions of the model and the sensitivity analysis

- All diplomats move on 1 January each year and spend an entire year in a location.
- All diplomats live in the US before and after their 20 year period of diplomatic assignments and their $PM_{2.5}$ exposure in the US is equal to the overall US annual mean concentration of $PM_{2.5}$ in those years.
- An inception lag is applied to the GBD C-R function when a diplomat move to a location with higher ambient $PM_{2.5}$ concentration compared to the prior location by 5 $\mu g/m^3$ or more.
- A cessation lag is applied to the GBD C-R function when a diplomat move to a location with lower ambient $PM_{2.5}$ concentration compared to the prior location by 5 $\mu g/m^3$ or more.
- When a diplomat move to a location with a change in ambient $PM_{2.5}$ concentration +/-5 ug/m^3, the current lag is cancelled, and a new lag is applied to take into account the difference between the RR in the new location and the evolved RR in the prior year in the prior location.
- Exposure to $PM_{2.5}$ is estimated by city averaged annual $PM_{2.5}$ concentration without considering the time spent outdoors or indoors, or activities including cooking or outdoor exercise that could potentially lead to a higher personal exposure to $PM_{2.5}$.
- The GBD C-R functions apply to the US diplomatic population.
- Baseline mortality for the US diplomatic corps population is same as that for the US population, reflected in the US mortality statistics in 2019.
- The $PM_{2.5}$ concentration and response relationship does not differ by sources of $PM_{2.5}$.
- For child assignment profiles, $PM_{2.5}$ exposure begins at birth excluding the pre-natal exposure period and continues until age 20 years in order to maintain the same duration of exposure among the three age groups studied.



Appendix Figure 1: Global Burden of Disease 2019 concentration-response (C-R) functions for lung cancer, lower respiratory infection (LRI), type two diabetes mellitus, chronic obstructive pulmonary disease (COPD), stroke for a 45 year old and ischemic heart disease (IHD) for a 45 year old according to the ambient $PM_{2.5}$ concentration.

A – Inception Lags



B – Cessation Lags

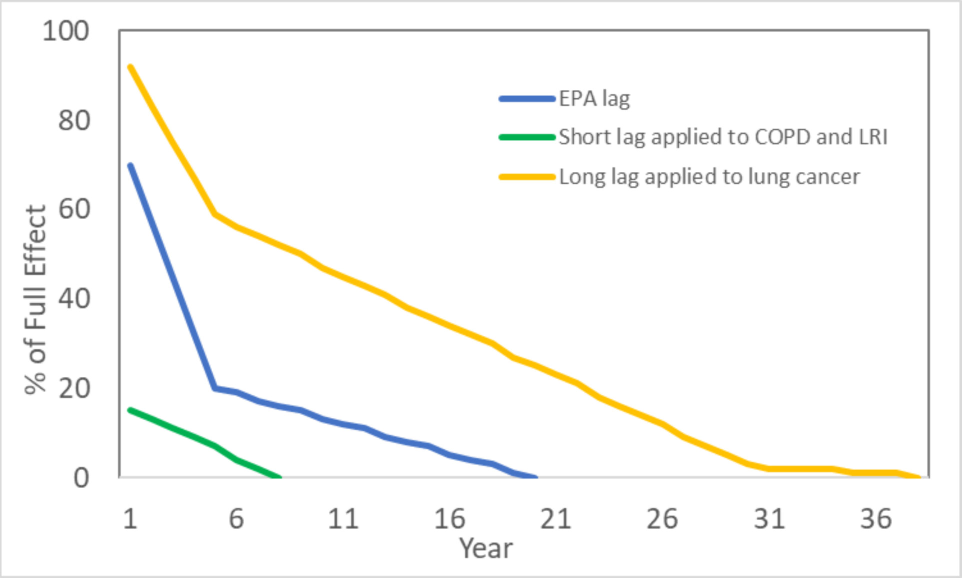


Figure A.2: Inception (A) and Cessation (B) lags used in the model and in the sensitivity analysis. The US EPA 20 year lag (blue) is the basis for the model and alternative lags used in the sensitivity analysis.

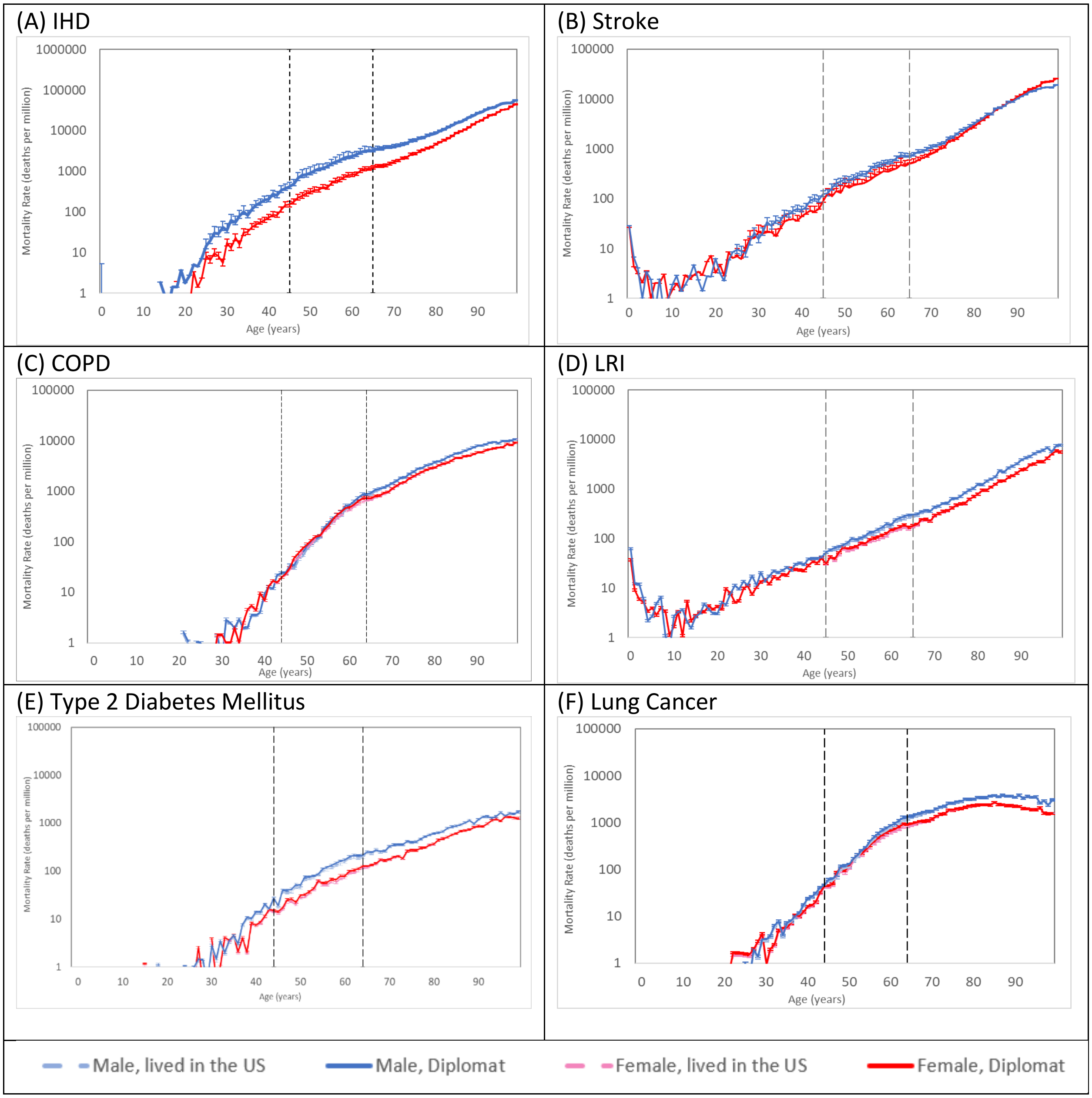


Figure A.3: Mortality rates (deaths per million) for (A) IHD (B) Stroke (C) COPD (D) LRI (E) type 2 DM and (F) lung cancer for an older diplomat during Assignment 1 (Standard A assignment) from age 45-64 years (solid line) and the rate for a person of the same age who lived in the United States (dashed line). The mortality rates are included for a male (blue) and female (red). Error bars represent the upper and lower confidence intervals for the mortality rates. The beginning and end of the 20-year period with diplomatic assignments are indicated by vertical dashed lines.

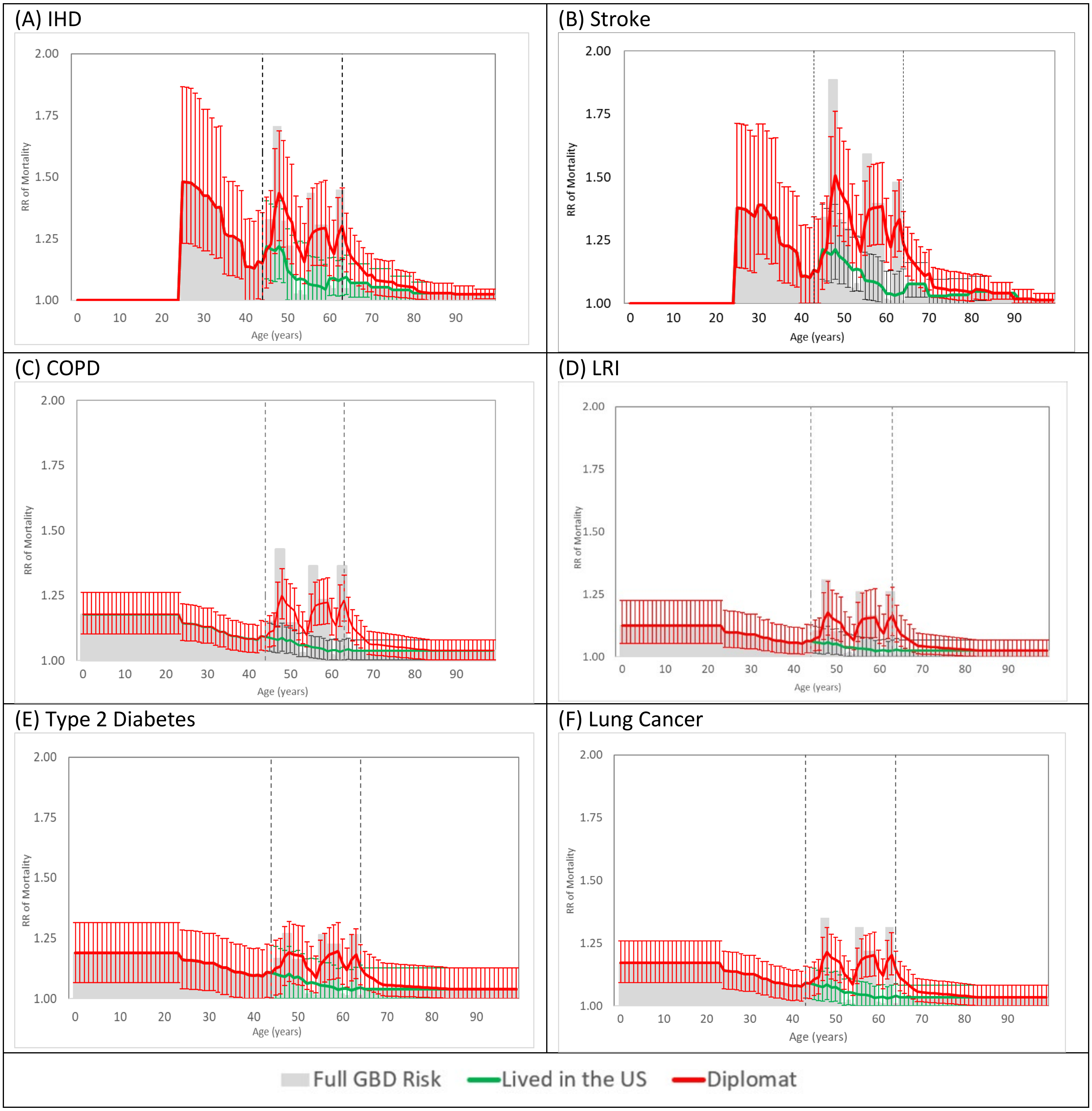


Figure A.4: Assignment 1, "Standard A" assignment, older diplomat; lagged risk relative (RR) of mortality for (A) IHD (B) stroke (C) COPD (D) LRI (E) type 2 diabetes mellitus and (F) lung cancer for a diplomat and the corresponding RR for a person of comparable age living in the US. The beginning and end of the 20 year period with diplomatic assignments is indicated by vertical dashed lines.

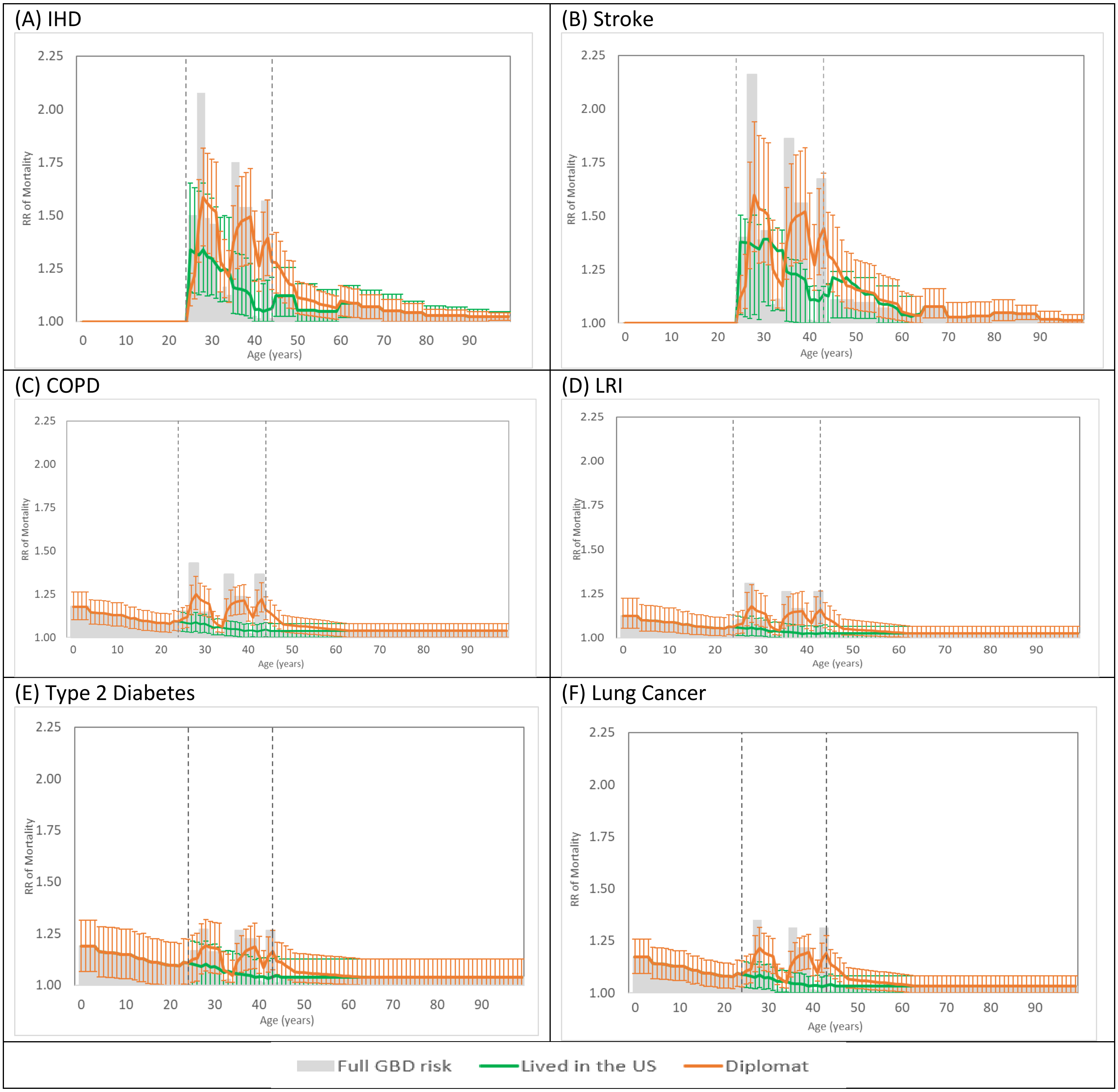


Figure A.5: Assignment 1, "Standard A" assignment, young diplomat; lagged risk relative (RR) of mortality for (A) IHD (B) stroke (C) COPD (D) LRI (E) type 2 diabetes mellitus and (F) lung cancer for a diplomat and the corresponding RR for a person of comparable age living in the US. The beginning and end of the 20 year period with diplomatic assignments is indicated by vertical dashed lines.

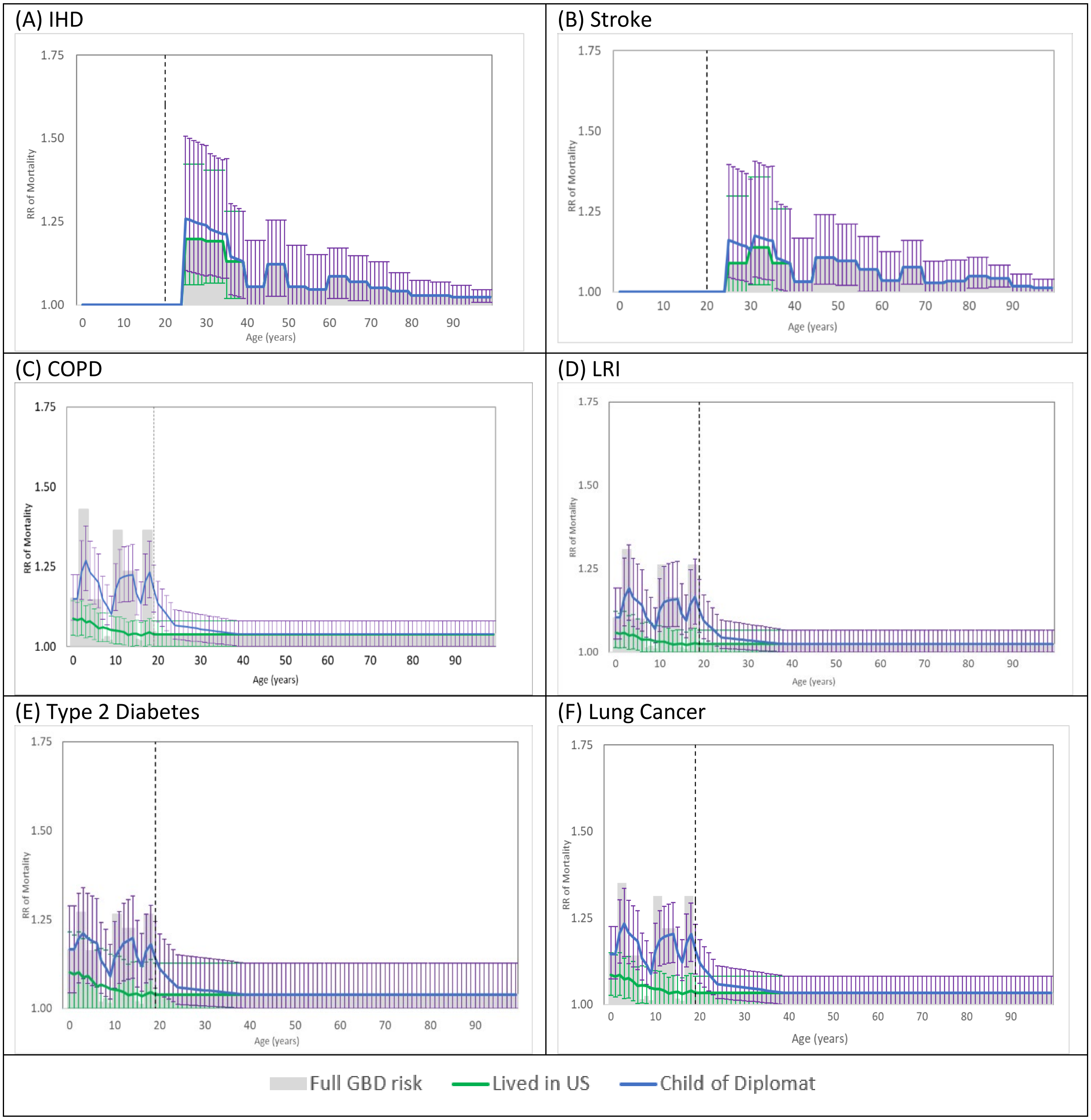


Figure A.6: Assignment 1, "Standard A" assignment, child of a diplomat; lagged risk relative (RR) of mortality for (A) IHD (B) stroke (C) COPD (D) LRI (E) type 2 diabetes mellitus and (F) lung cancer for the child a diplomat and the corresponding RR for a person of comparable age living in the US. The beginning and end of the 20 year period with diplomatic assignments is indicated by vertical dashed line.

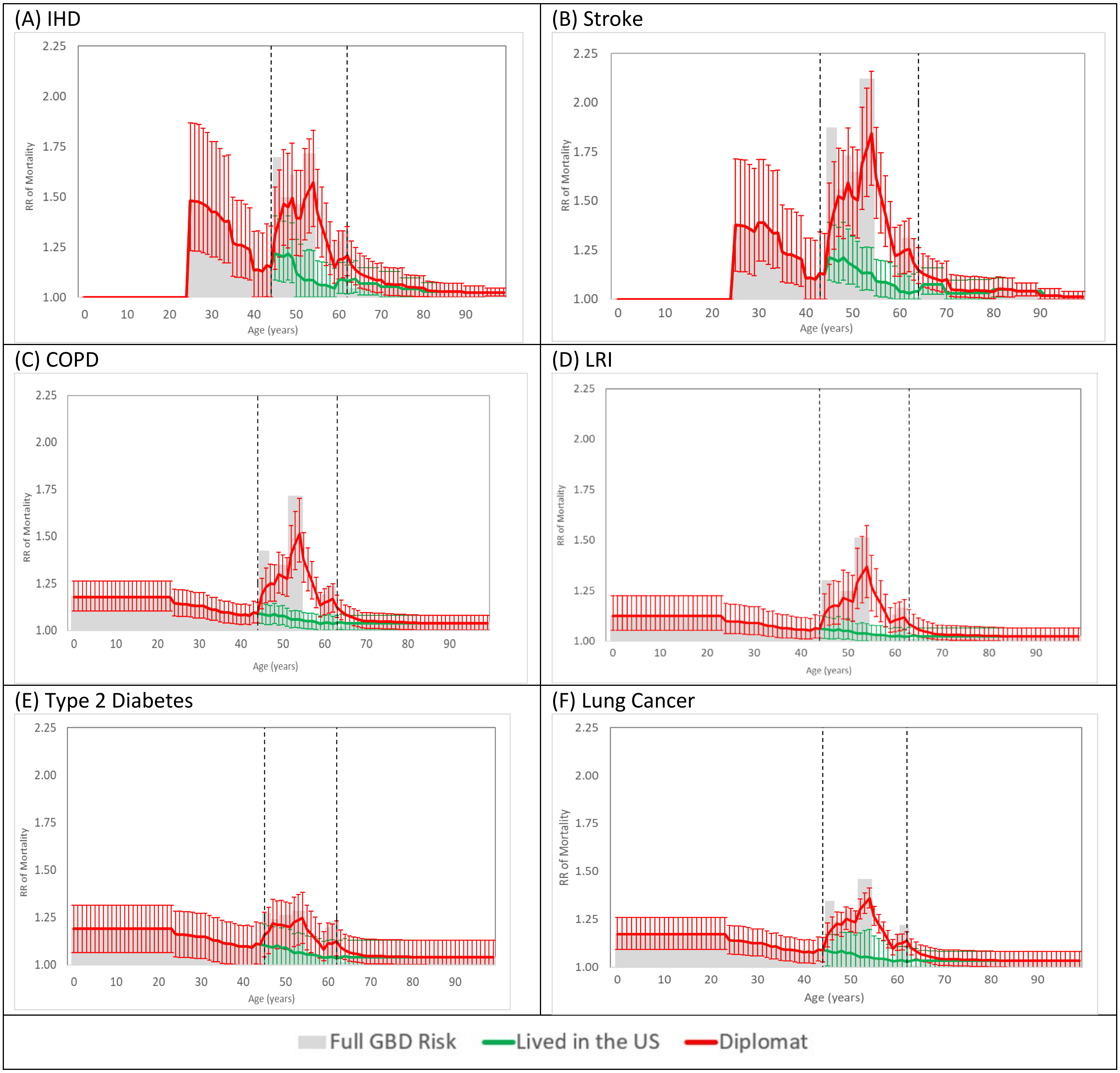


Figure A.7: Assignment 2, "Standard B" assignment, older diplomat; lagged risk relative (RR) of mortality for (A) IHD (B) stroke (C) COPD (D) LRI (E) type 2 diabetes mellitus and (F) lung cancer for a diplomat and the corresponding RR for a person of comparable age living in the US. The beginning and end of the 20 year period with diplomatic assignments is indicated by vertical dashed lines.

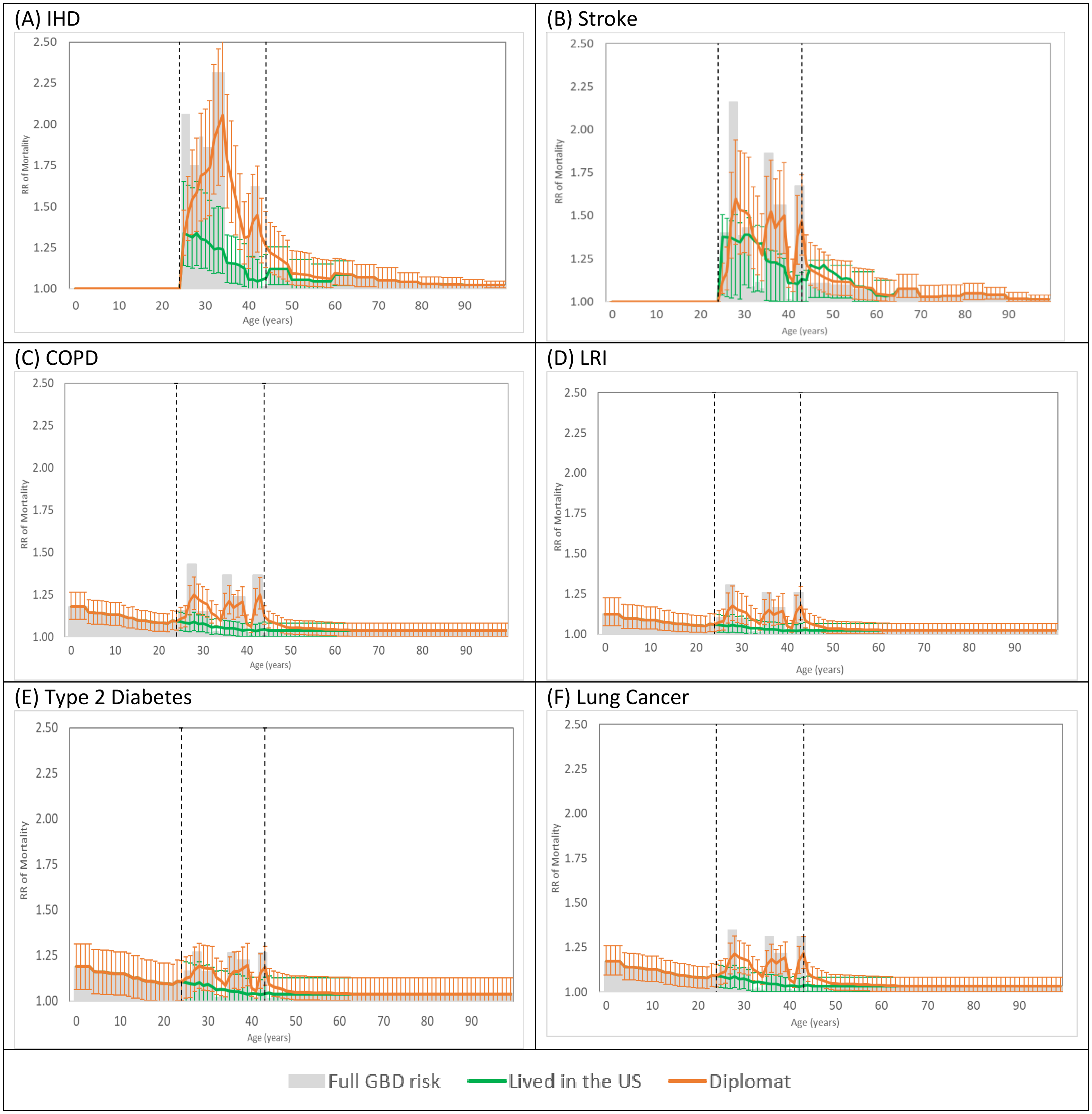


Figure A.8: Assignment 2, "Standard B" assignment, young diplomat; lagged risk relative (RR) of mortality for (A) IHD (B) stroke (C) COPD (D) LRI (E) type 2 diabetes mellitus and (F) lung cancer for a diplomat and the corresponding RR for a person of comparable age living in the US. The beginning and end of the 20 year period with diplomatic assignments is indicated by vertical dashed lines.

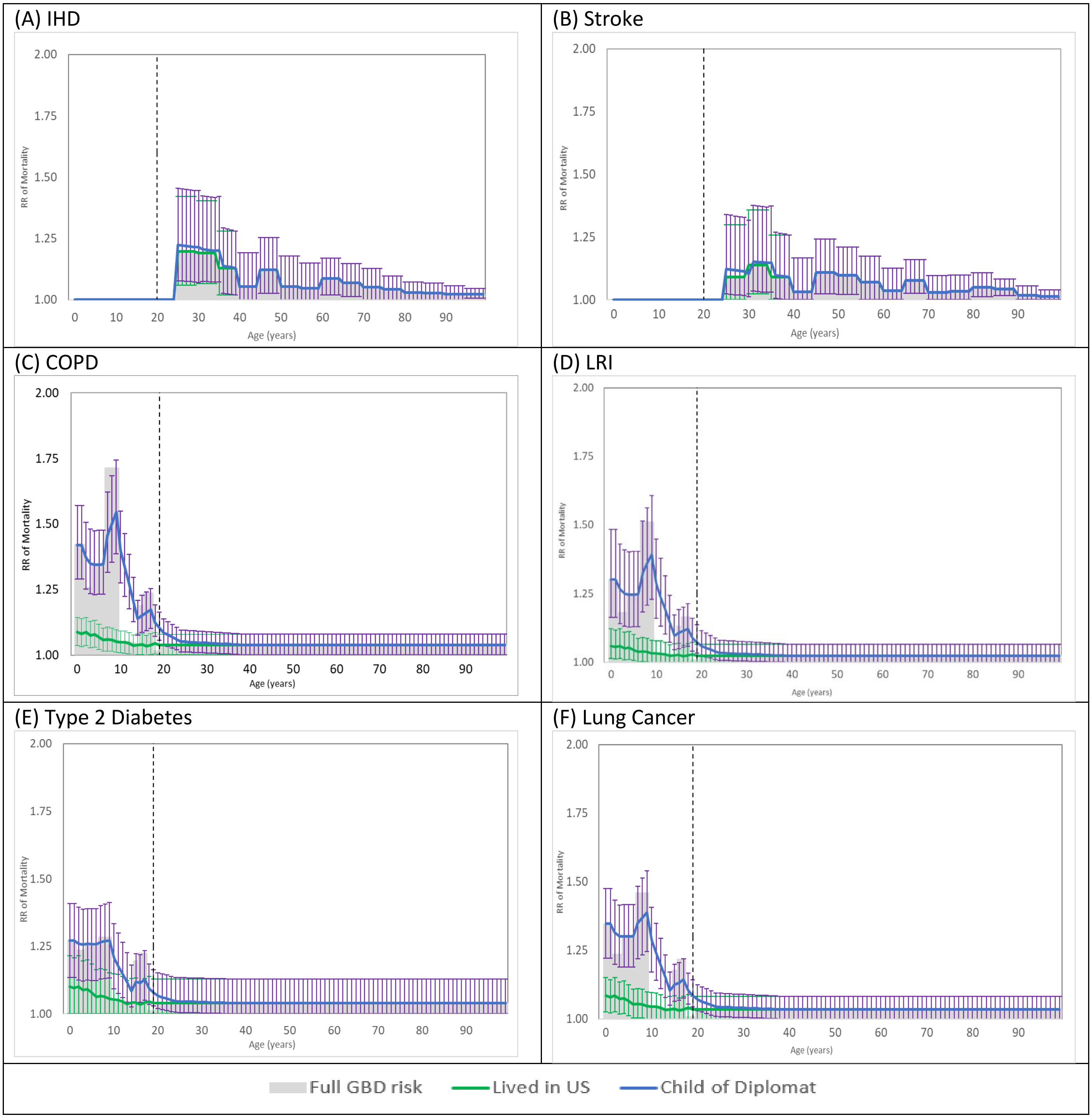


Figure A.9: Assignment 2, "Standard B" assignment, child of a diplomat; lagged risk relative (RR) of mortality for (A) IHD (B) stroke (C) COPD (D) LRI (E) type 2 diabetes mellitus and (F) lung cancer for the child of a diplomat and the corresponding RR for a person of comparable age living in the US. The beginning and end of the 20 year period with diplomatic assignments is indicated by vertical dashed lines.

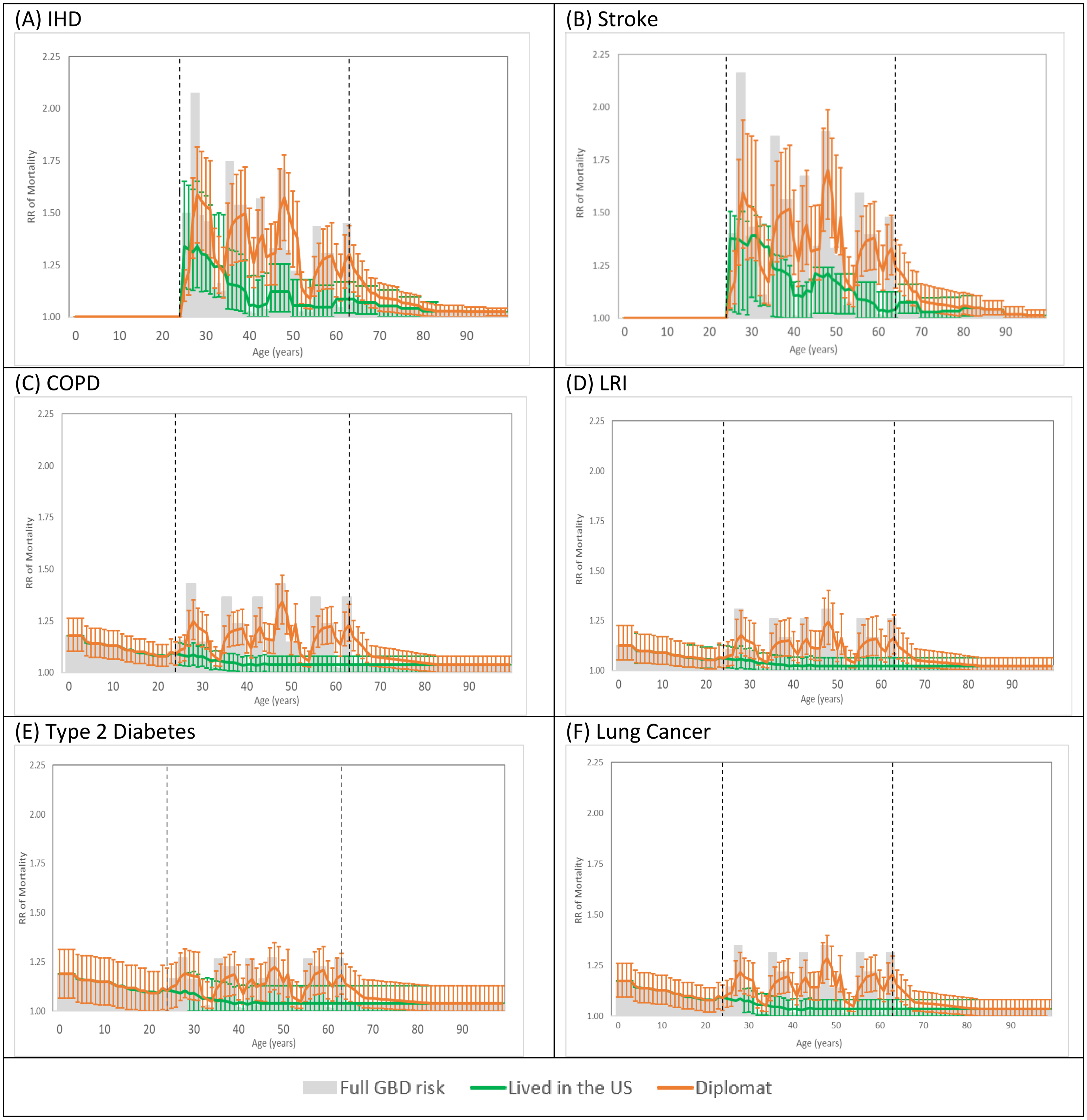


Figure A.10: Assignment 3, “Standard A x 2” assignment, young diplomat; lagged risk relative (RR) of mortality for (A) IHD (B) stroke (C) COPD (D) LRI (E) type 2 diabetes mellitus and (F) lung cancer for a diplomat and the corresponding RR for a person of comparable age living in the US. The beginning and end of the 40 year period with diplomatic assignments is indicated by vertical dashed lines.

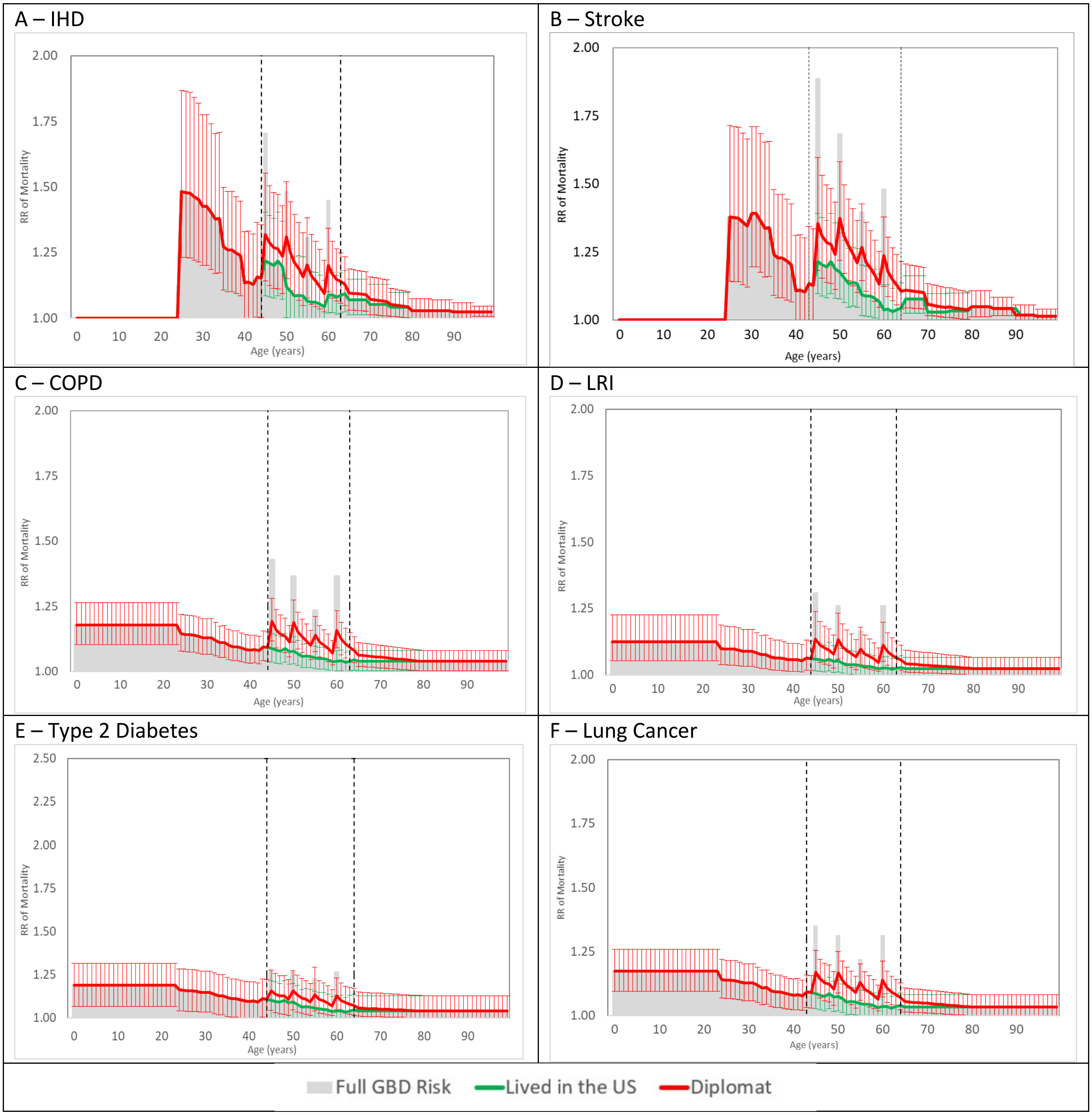


Figure A.11: Assignment 4, older diplomat in "High 1 year & low 3 years cycle" assignment; lagged risk relative (RR) of mortality for (A) IHD (B) stroke (C) COPD (D) LRI (E) type 2 diabetes mellitus and (F) lung cancer for a diplomat and the corresponding RR for a person of comparable age living in the US. The beginning and end of the 20 year period with diplomatic assignments is indicated by vertical dashed lines.

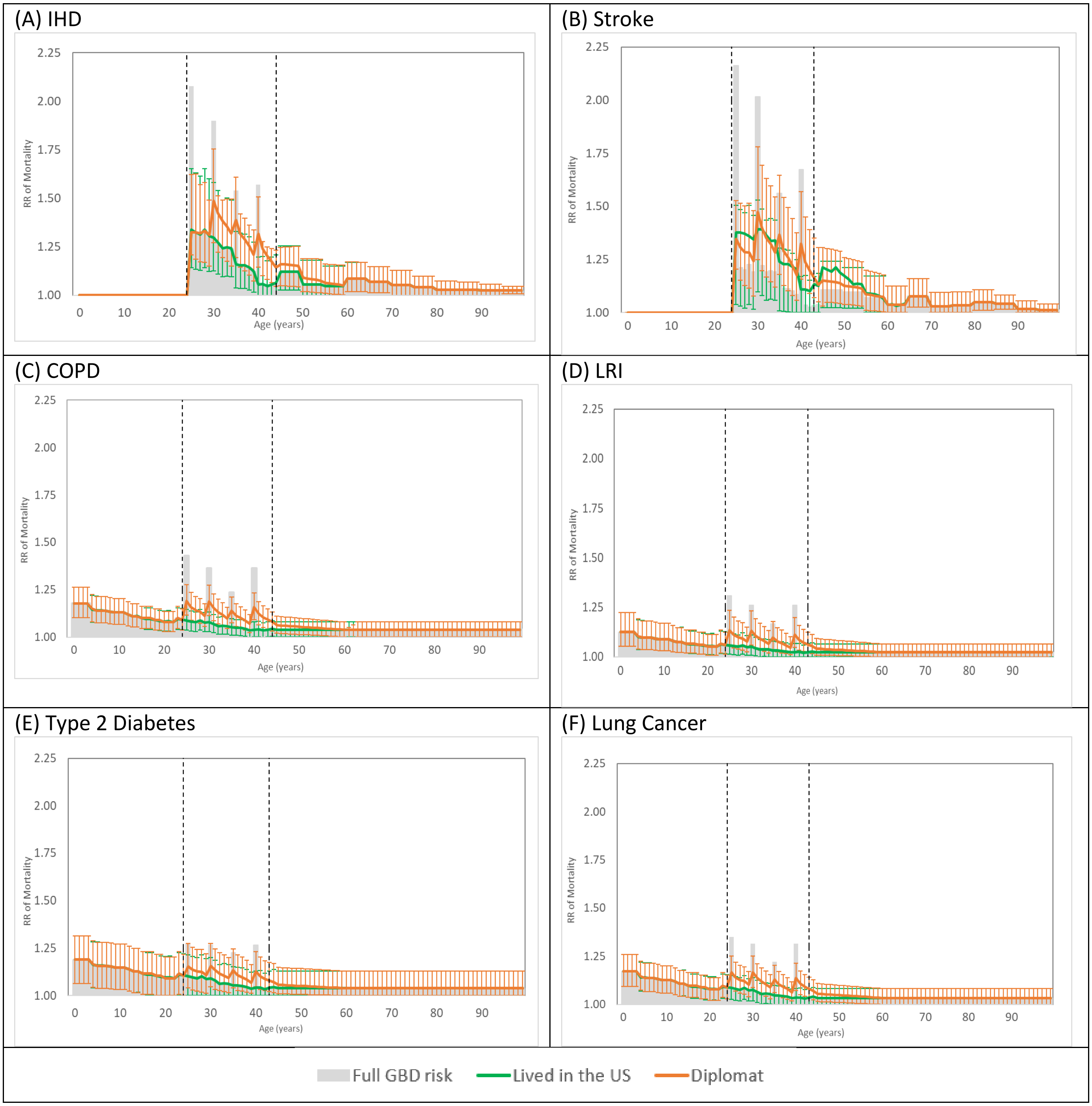


Figure A.12: Assignment 4, young diplomat in "High 1 year & low 3 years cycle" assignment; lagged risk relative (RR) of mortality for (A) IHD (B) stroke (C) COPD (D) LRI (E) type 2 diabetes mellitus and (F) lung cancer for a diplomat and the corresponding RR for a person of comparable age living in the US. The beginning and end of the 20 year period with diplomatic assignments is indicated by vertical dashed lines.

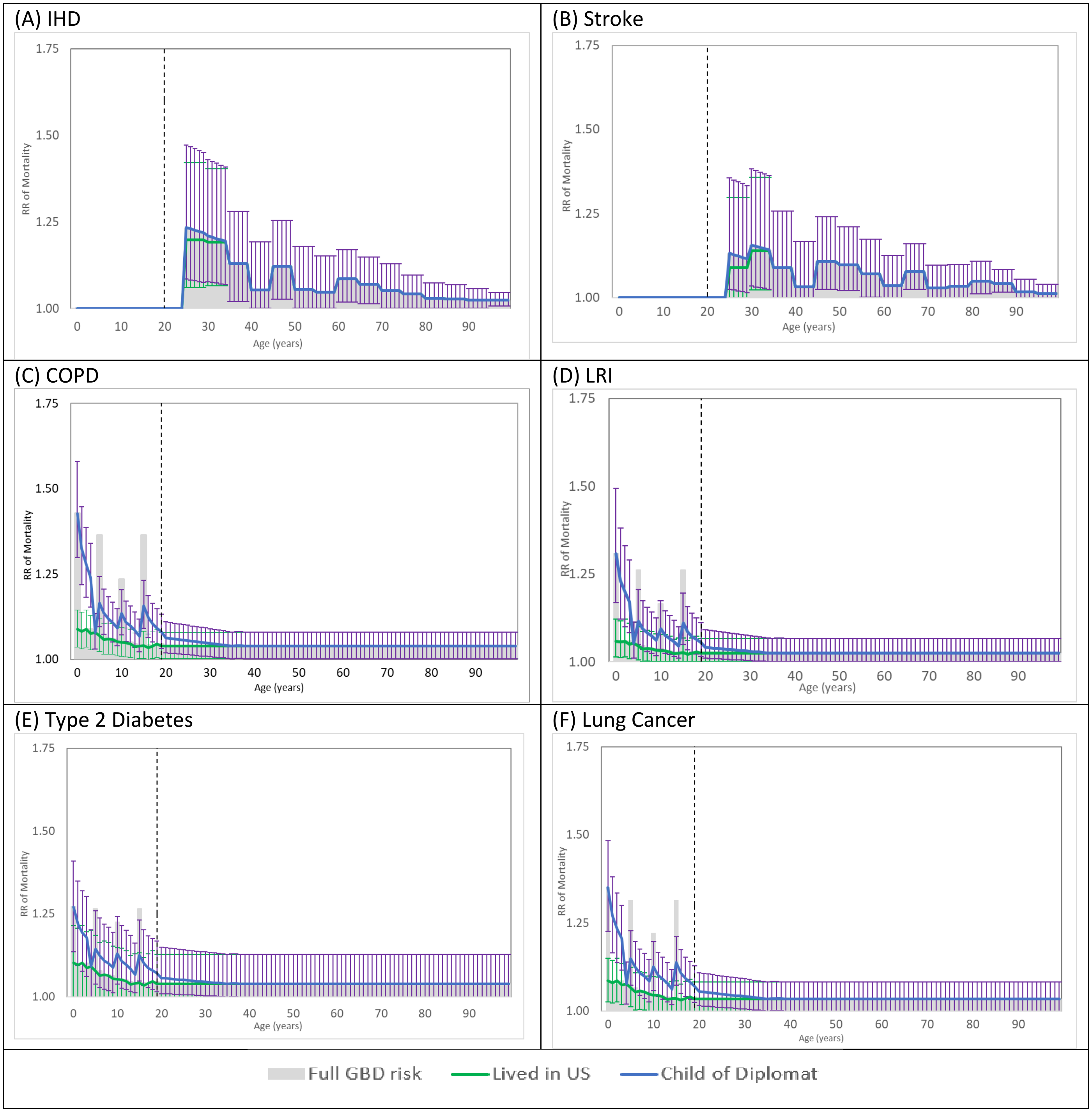


Figure A.13: Assignment 4, child of a diplomat in “High 1 year & low 3 years cycle” assignment; lagged risk relative (RR) of mortality for (A) IHD (B) stroke (C) COPD (D) LRI (E) type 2 diabetes mellitus and (F) lung cancer for the child of a diplomat and the corresponding RR for a person of comparable age living in the US. The beginning and end of the 20 year period with diplomatic assignments is indicated by vertical dashed lines.

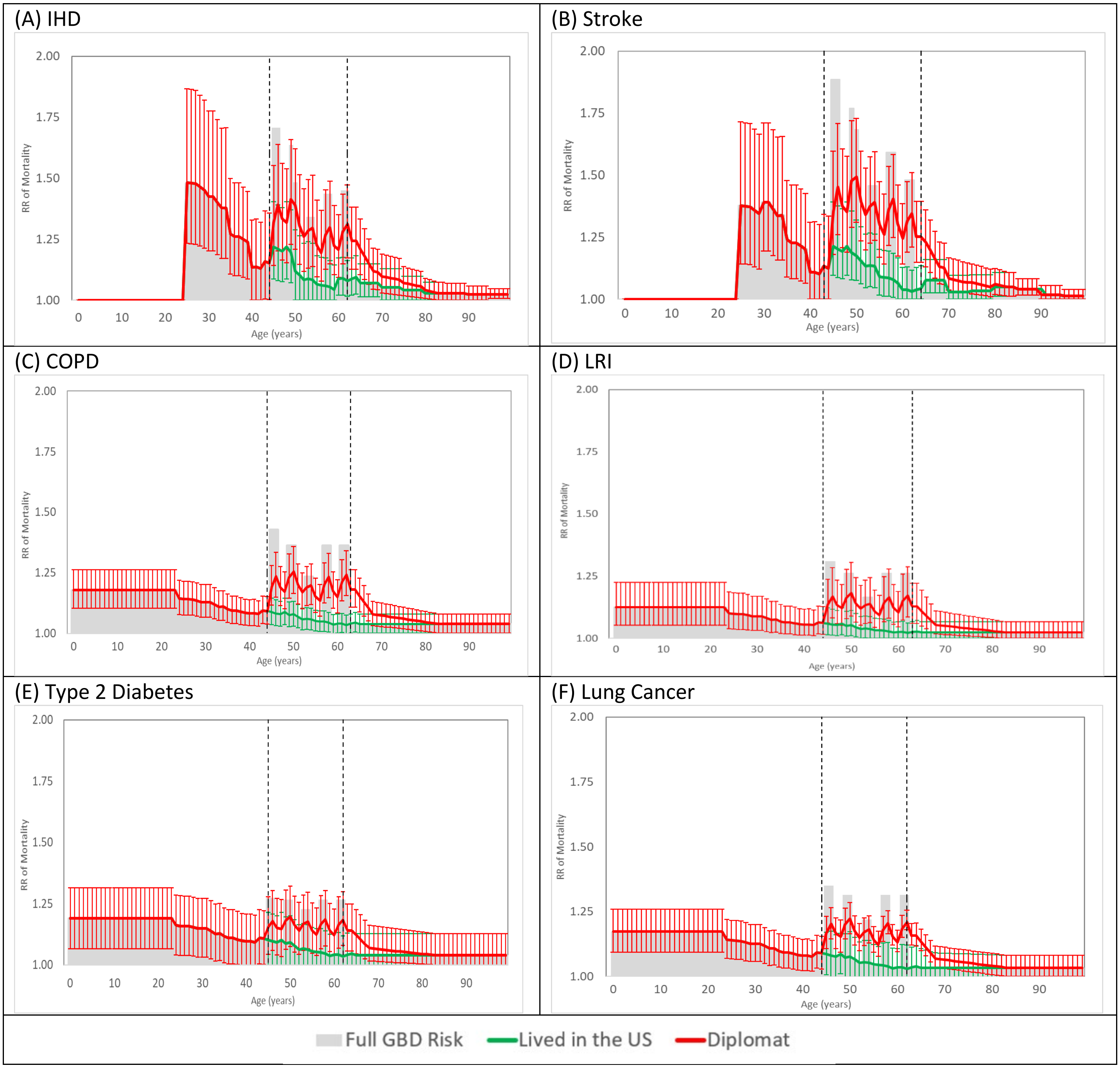


Figure A.14: Assignment 5, older diplomat in "High 2 years & low 2 years cycle" assignment; lagged risk relative (RR) of mortality for (A) IHD (B) stroke (C) COPD (D) LRI (E) type 2 diabetes mellitus and (F) lung cancer for a diplomat and the corresponding RR for a person of comparable age living in the US. The beginning and end of the 20 year period with diplomatic assignments is indicated by vertical dashed lines.

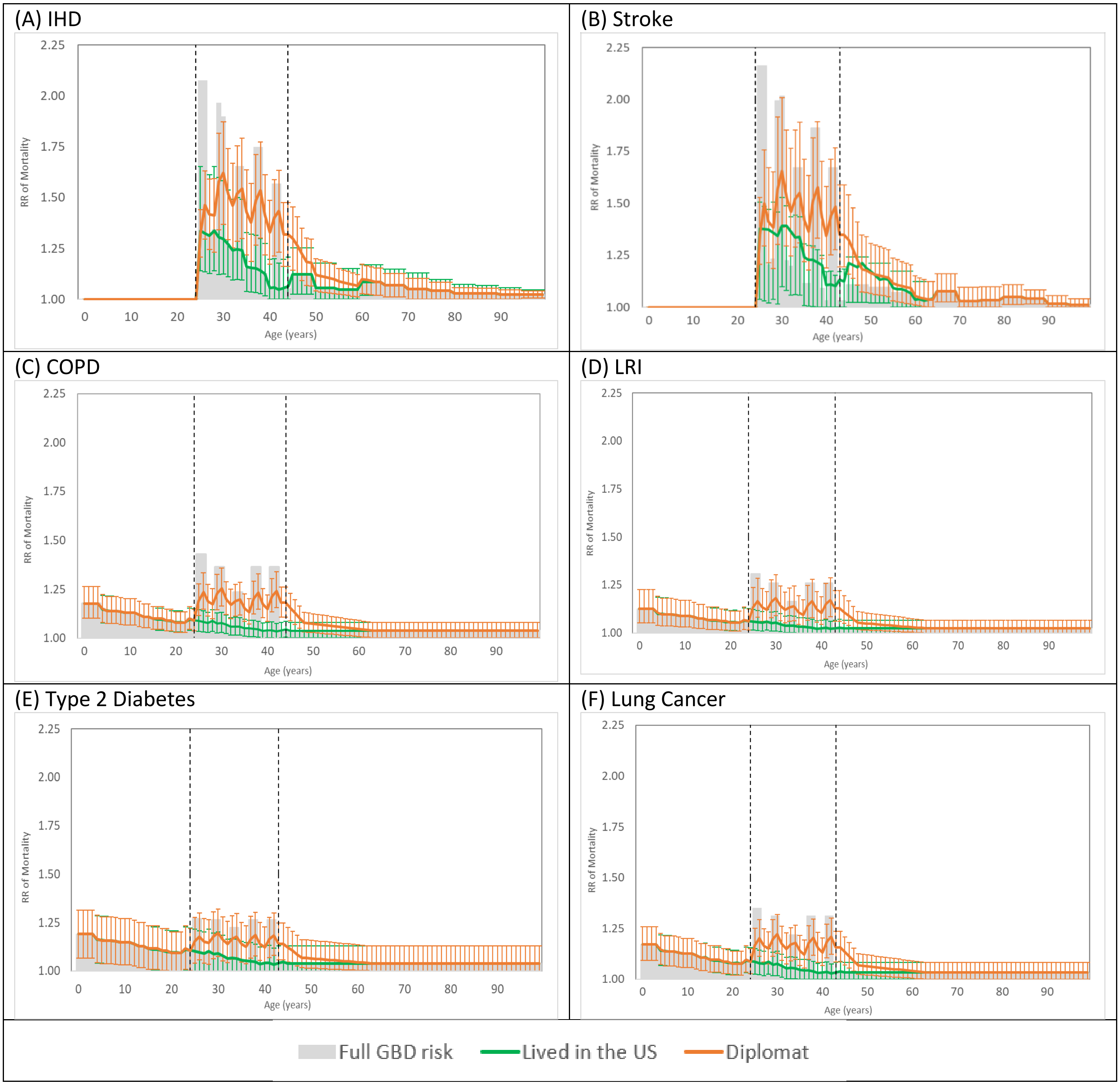


Figure A.15: Assignment 5, young diplomat in "High 2 years & low 2 years cycle" assignment; lagged risk relative (RR) of mortality for (A) IHD (B) stroke (C) COPD (D) LRI (E) type 2 diabetes mellitus and (F) lung cancer for a diplomat and the corresponding RR for a person of comparable age living in the US. The beginning and end of the 20 year period with diplomatic assignments is indicated by vertical dashed lines.

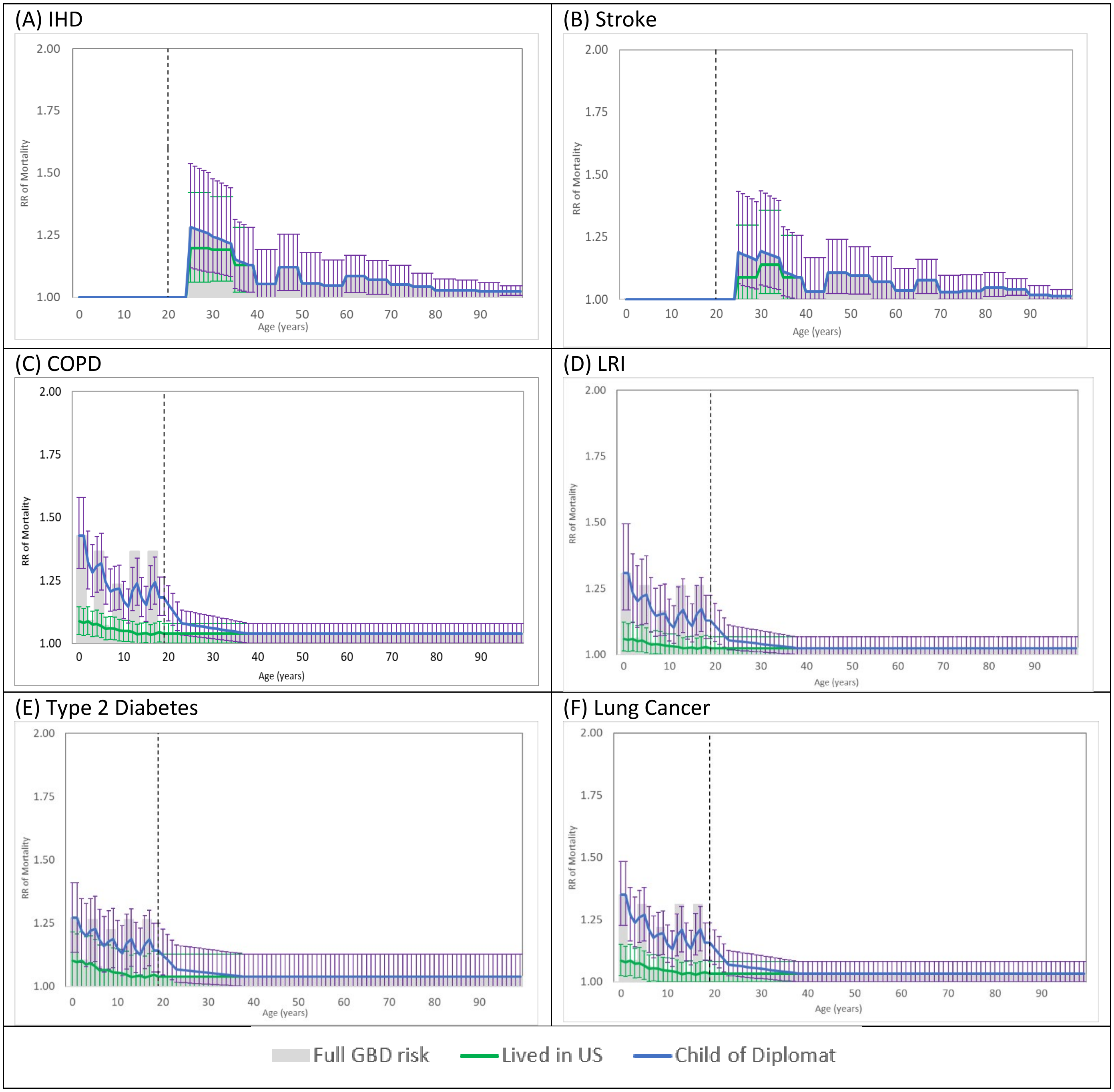


Figure A.16: Assignment 5, child of a diplomat in "High 2 years & low 2 years cycle" assignment; lagged risk relative (RR) of mortality for (A) IHD (B) stroke (C) COPD (D) LRI (E) type 2 diabetes mellitus and (F) lung cancer for the child of a diplomat and the corresponding RR for a person of comparable age living in the US. The beginning and end of the 20 year period with diplomatic assignments is indicated by vertical dashed lines.

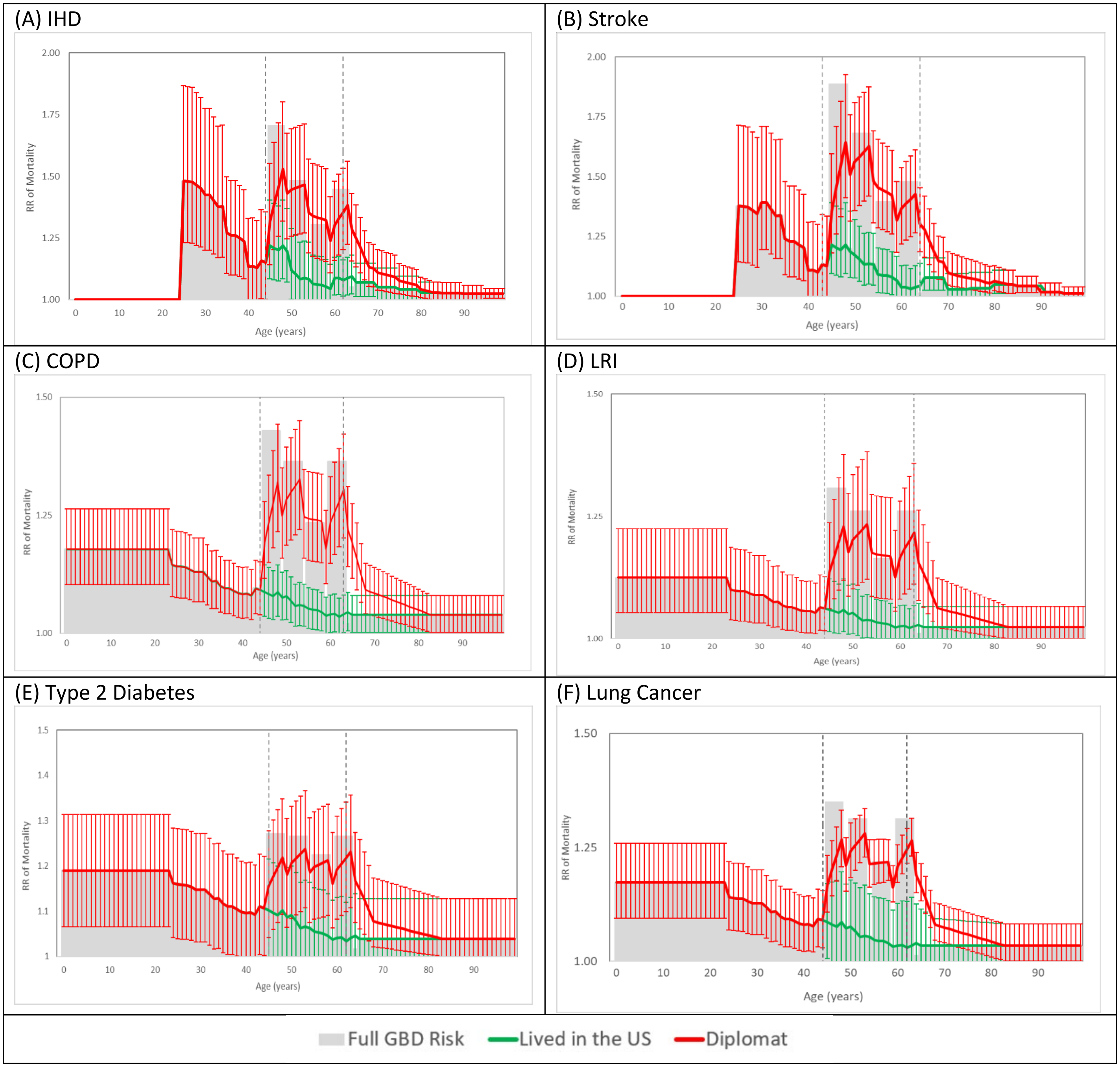


Figure A.17: Assignment 6, older diplomat in "High 3 years & low 1 years cycle" assignment; lagged risk relative (RR) of mortality for (A) IHD (B) stroke (C) COPD (D) LRI (E) type 2 diabetes mellitus and (F) lung cancer for a diplomat and the corresponding RR for a person of comparable age living in the US. The beginning and end of the 20 year period with diplomatic assignments is indicated by vertical dashed lines.

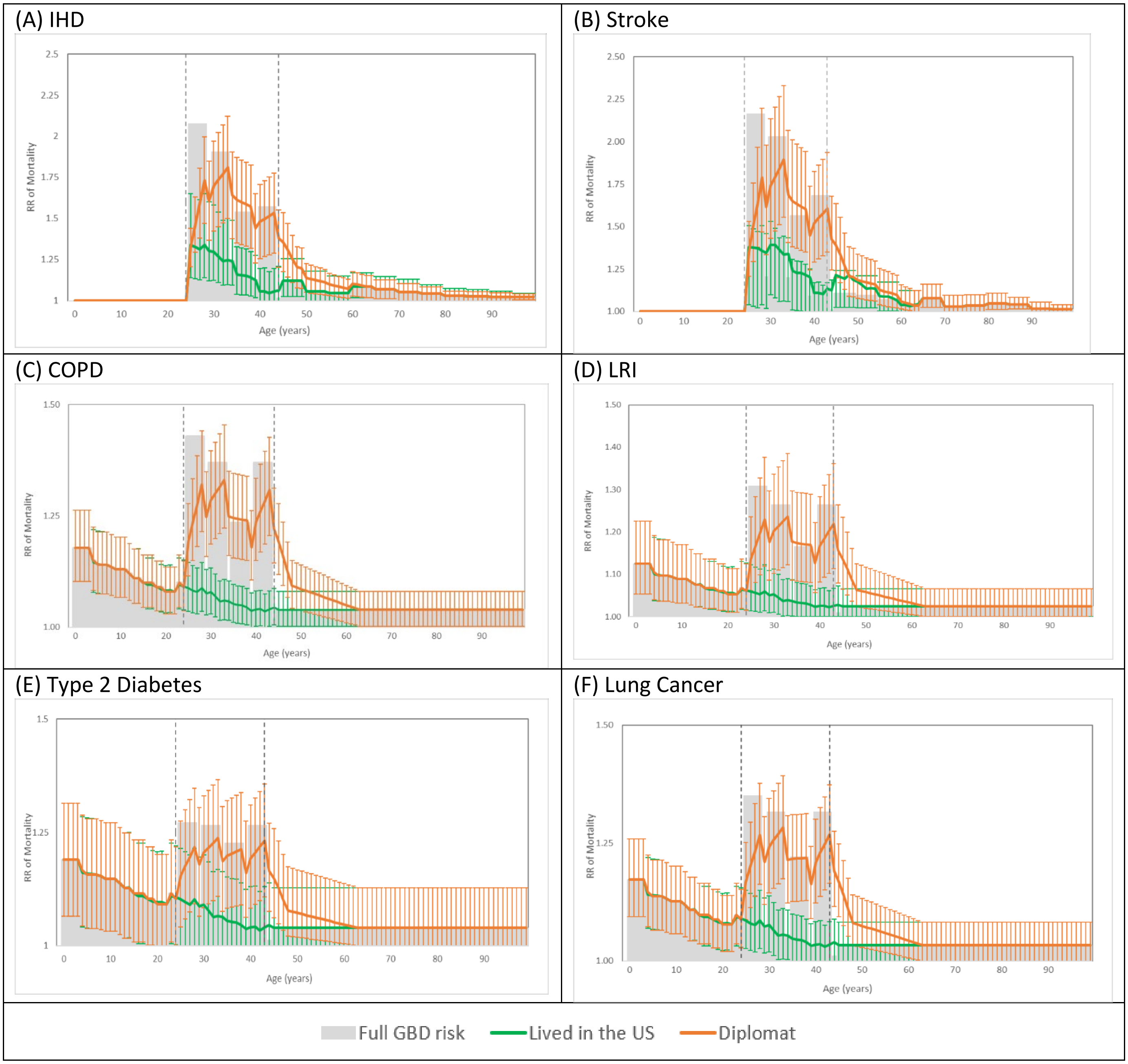
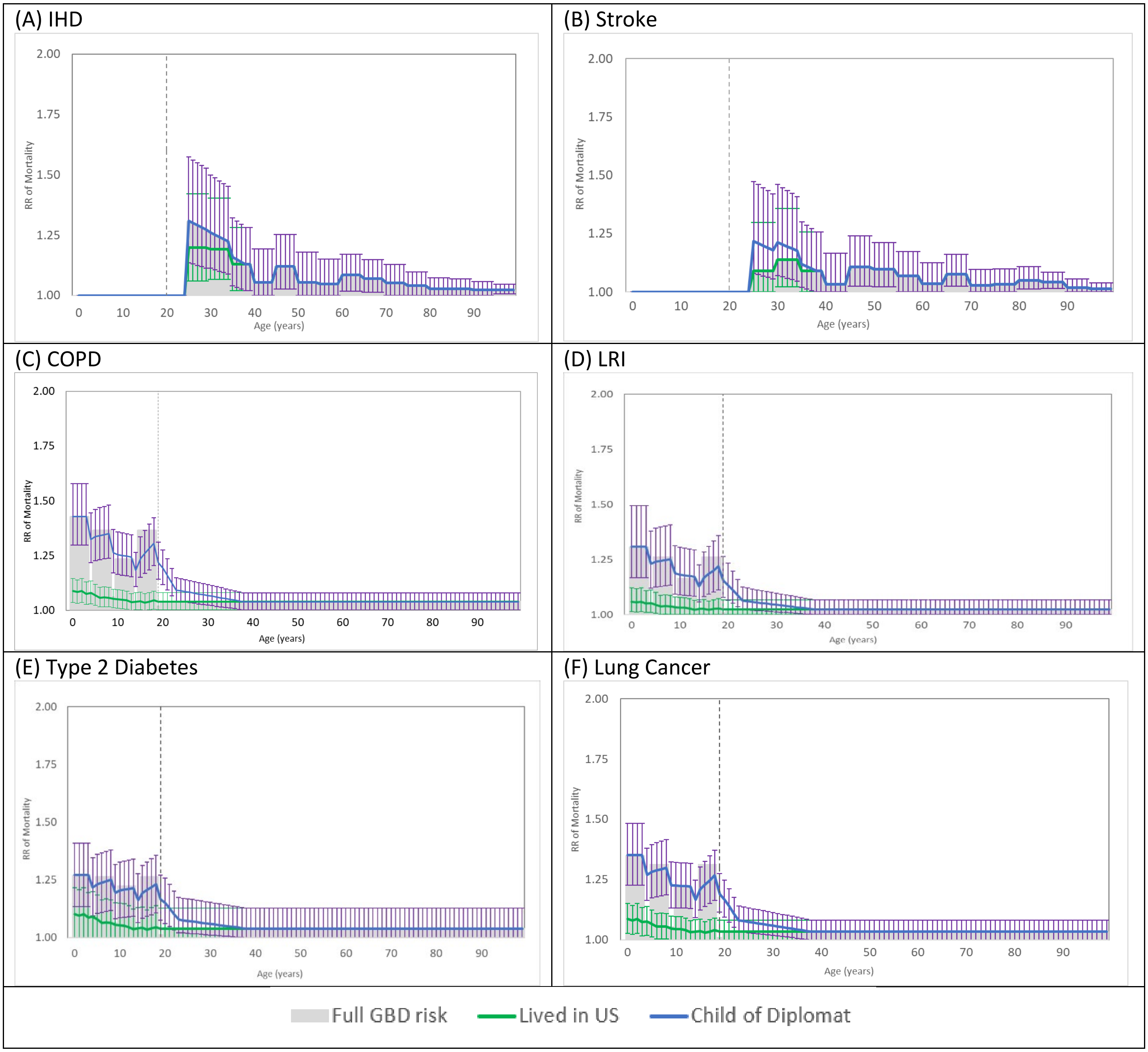


Figure A.18: Assignment 6, young diplomat in "High 3 years & low 1 years cycle" assignment; lagged risk relative (RR) of mortality for (A) IHD (B) stroke (C) COPD (D) LRI (E) type 2 diabetes mellitus and (F) lung cancer for a diplomat and the corresponding RR for a person of comparable age living in the US. The beginning and end of the 20 year period with diplomatic assignments is indicated by vertical dashed lines.


(A) IHD

(B) Stroke

(C) COPD

(D) LRI

(E) Type 2 Diabetes

(F) Lung Cancer

Figure A.19: Assignment 6, child of a diplomat in "High 3 years & low 1 years cycle" assignment; lagged risk relative (RR) of mortality for (A) IHD (B) stroke (C) COPD (D) LRI (E) type 2 diabetes mellitus and (F) lung cancer for the child of a diplomat and the corresponding RR for a person of comparable age living in the US. The beginning and end of the 20 year period with diplomatic assignments is indicated by vertical dashed lines.

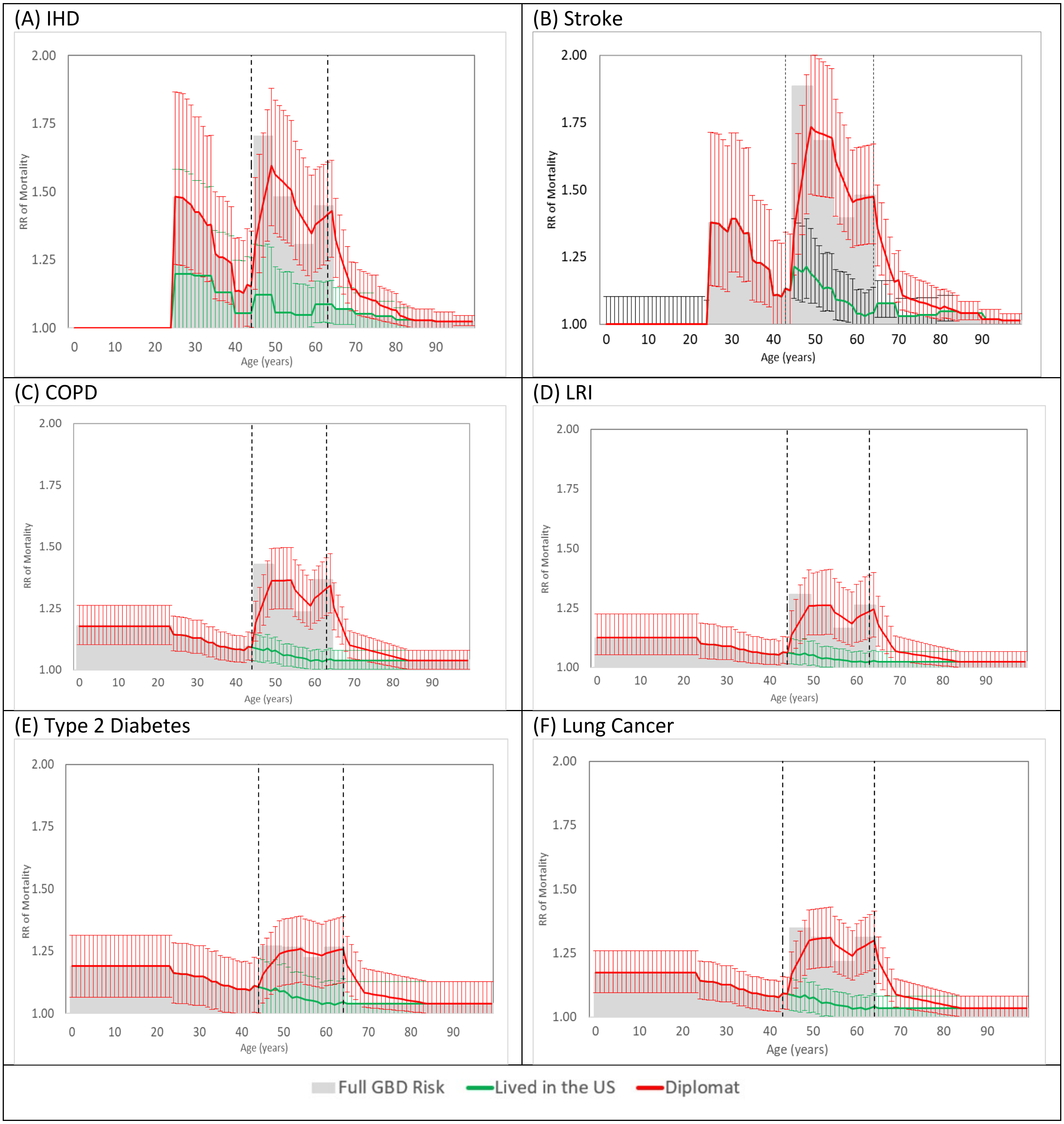
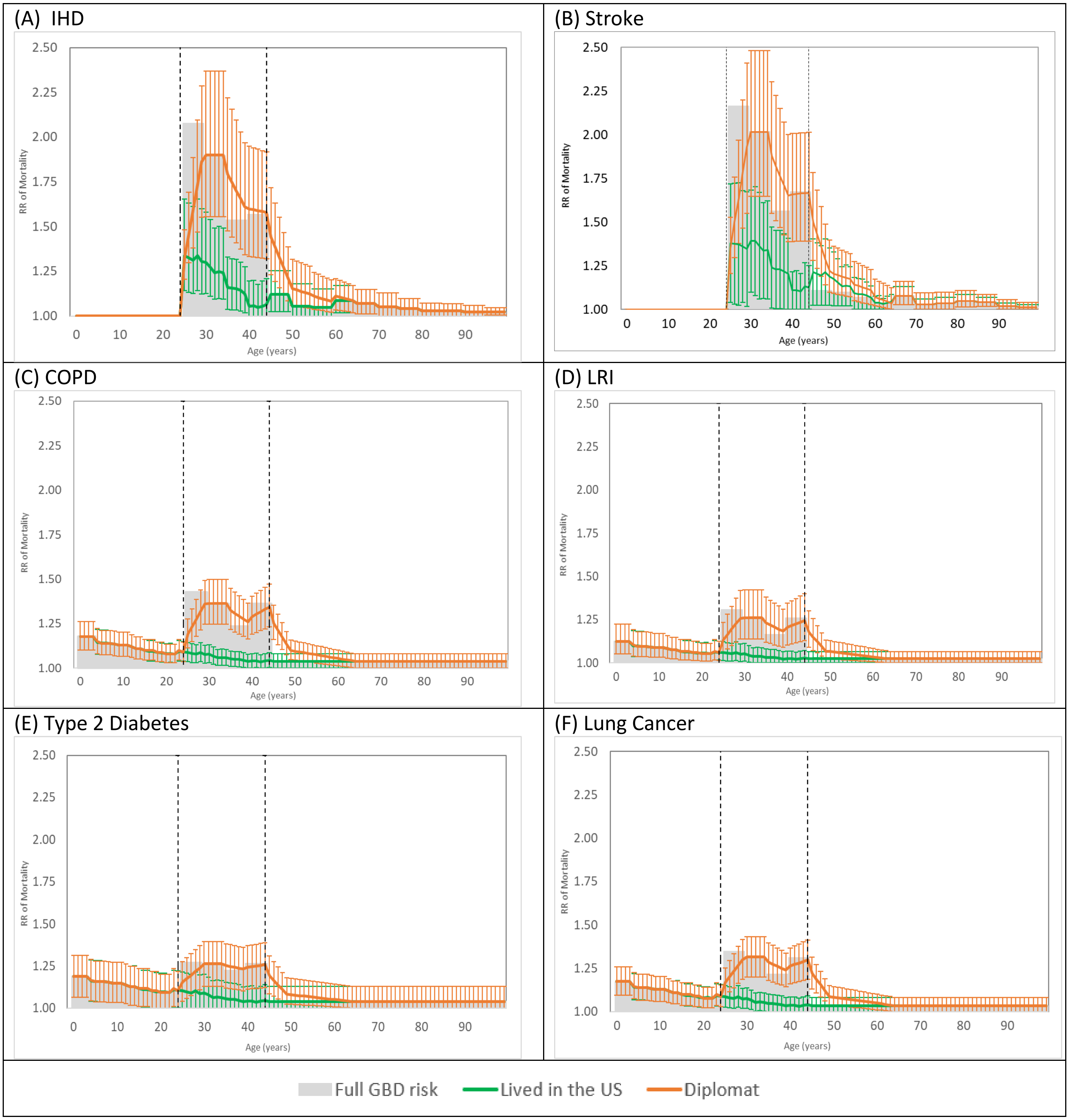


Figure A.20: Assignment 7, older diplomat in “High 4 years x 5” assignment; lagged risk relative (RR) of mortality for (A) IHD (B) stroke (C) COPD (D) LRI (E) type 2 diabetes mellitus and (F) lung cancer for a diplomat and the corresponding RR for a person of comparable age living in the US. The beginning and end of the 20 year period with diplomatic assignments is indicated by vertical dashed lines.


(A) IHD

(B) Stroke

(C) COPD

(D) LRI

(E) Type 2 Diabetes

(F) Lung Cancer

Figure A.21: Assignment 7, young diplomat in "High 4 years x 5" assignment; lagged risk relative (RR) of mortality for (A) IHD (B) stroke (C) COPD (D) LRI (E) type 2 diabetes mellitus and (F) lung cancer for a diplomat and the corresponding RR for a person of comparable age living in the US. The beginning and end of the 20 year period with diplomatic assignments is indicated by vertical dashed lines.

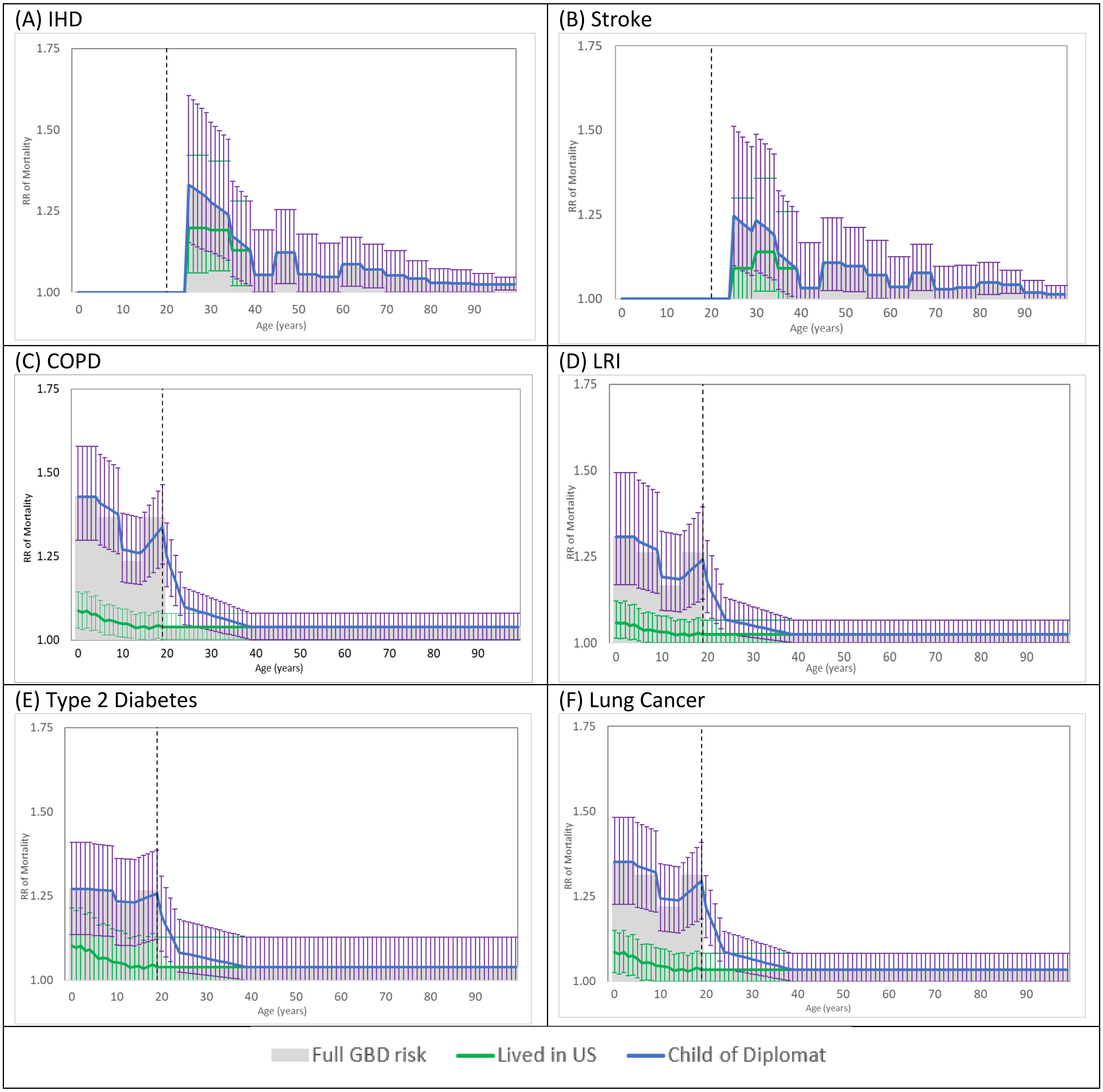


Figure A.22: Assignment 7, child of a diplomat in "High 4 years x 5" assignment; lagged risk relative (RR) of mortality for (A) IHD (B) stroke (C) COPD (D) LRI (E) type 2 diabetes mellitus and (F) lung cancer for the child of a diplomat and the corresponding RR for a person of comparable age living in the US. The beginning and end of the 20 year period with diplomatic assignments is indicated by vertical dashed lines.

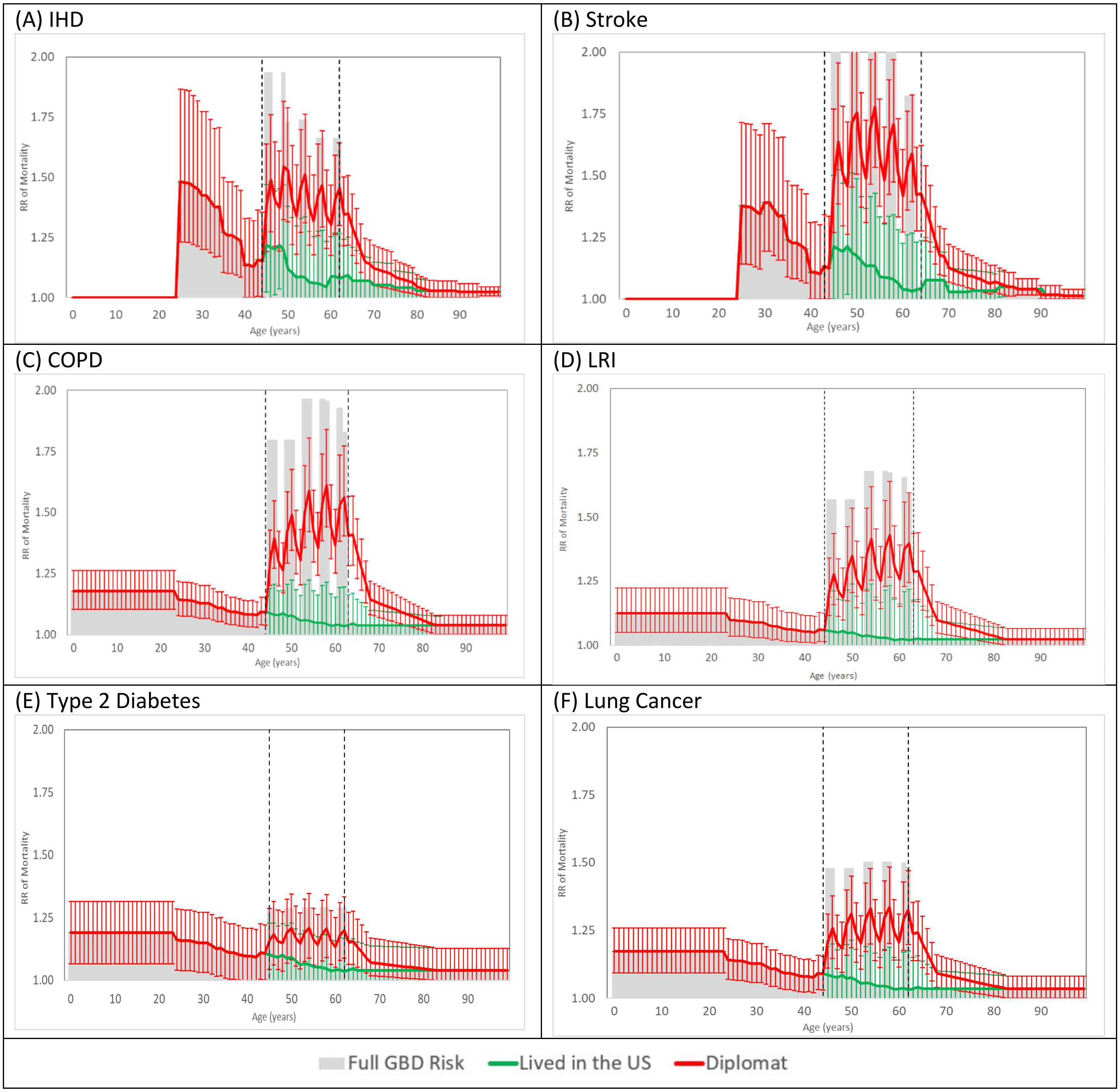


Figure A.23: Assignment 8, older diplomat in "Very high 2 years & low 2 years cycle" assignment; lagged risk relative (RR) of mortality for (A) IHD (B) stroke (C) COPD (D) LRI (E) type 2 diabetes mellitus and (F) lung cancer for a diplomat and the corresponding RR for a person of comparable age living in the US. The beginning and end of the 20 year period with diplomatic assignments is indicated by vertical dashed lines.

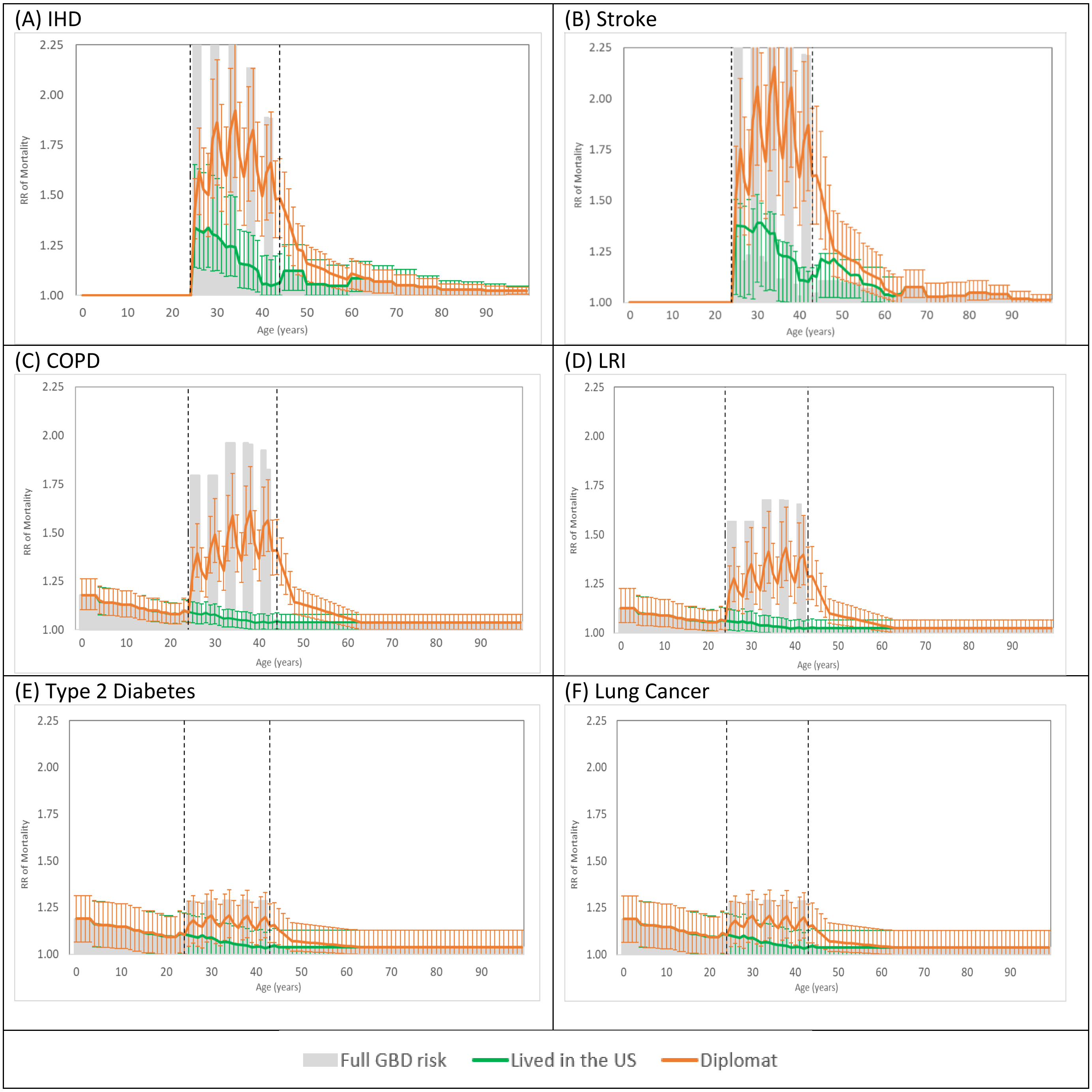


Figure A.24: Assignment 8, young diplomat in "Very high 2 years & low 2 years cycle" assignment; lagged risk relative (RR) of mortality for (A) IHD (B) stroke (C) COPD (D) LRI (E) type 2 diabetes mellitus and (F) lung cancer for a diplomat and the corresponding RR for a person of comparable age living in the US. The beginning and end of the 20 year period with diplomatic assignments is indicated by vertical dashed lines.

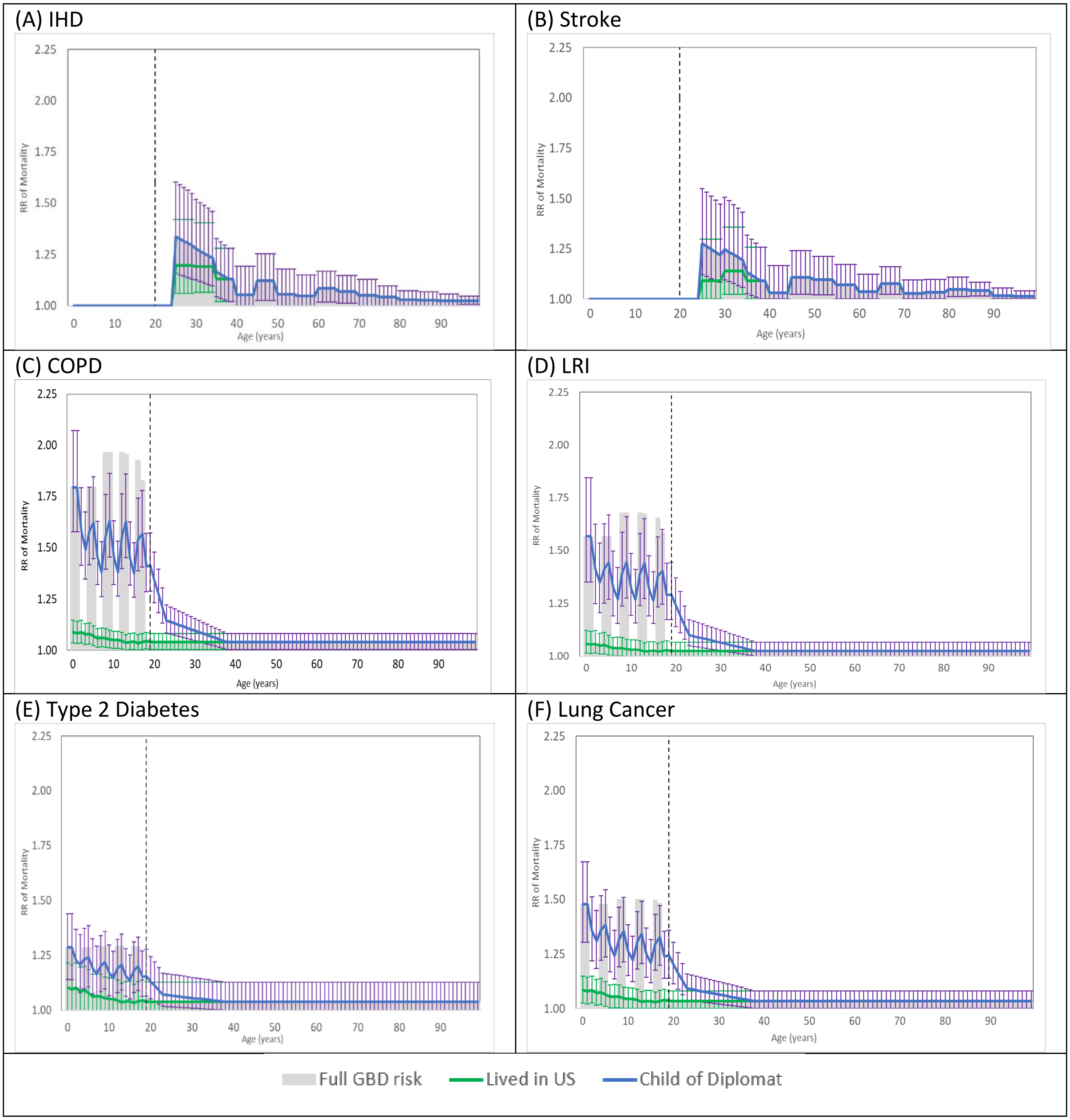


Figure A.25: Assignment 8, child of a diplomat in "Very high 2 years & low 2 years cycle" assignment; lagged risk relative (RR) of mortality for (A) IHD (B) stroke (C) COPD (D) LRI (E) type 2 diabetes mellitus and (F) lung cancer for the child of a diplomat and the corresponding RR for a person of comparable age living in the US. The beginning and end of the 20 year period with diplomatic assignments is indicated by vertical dashed lines.

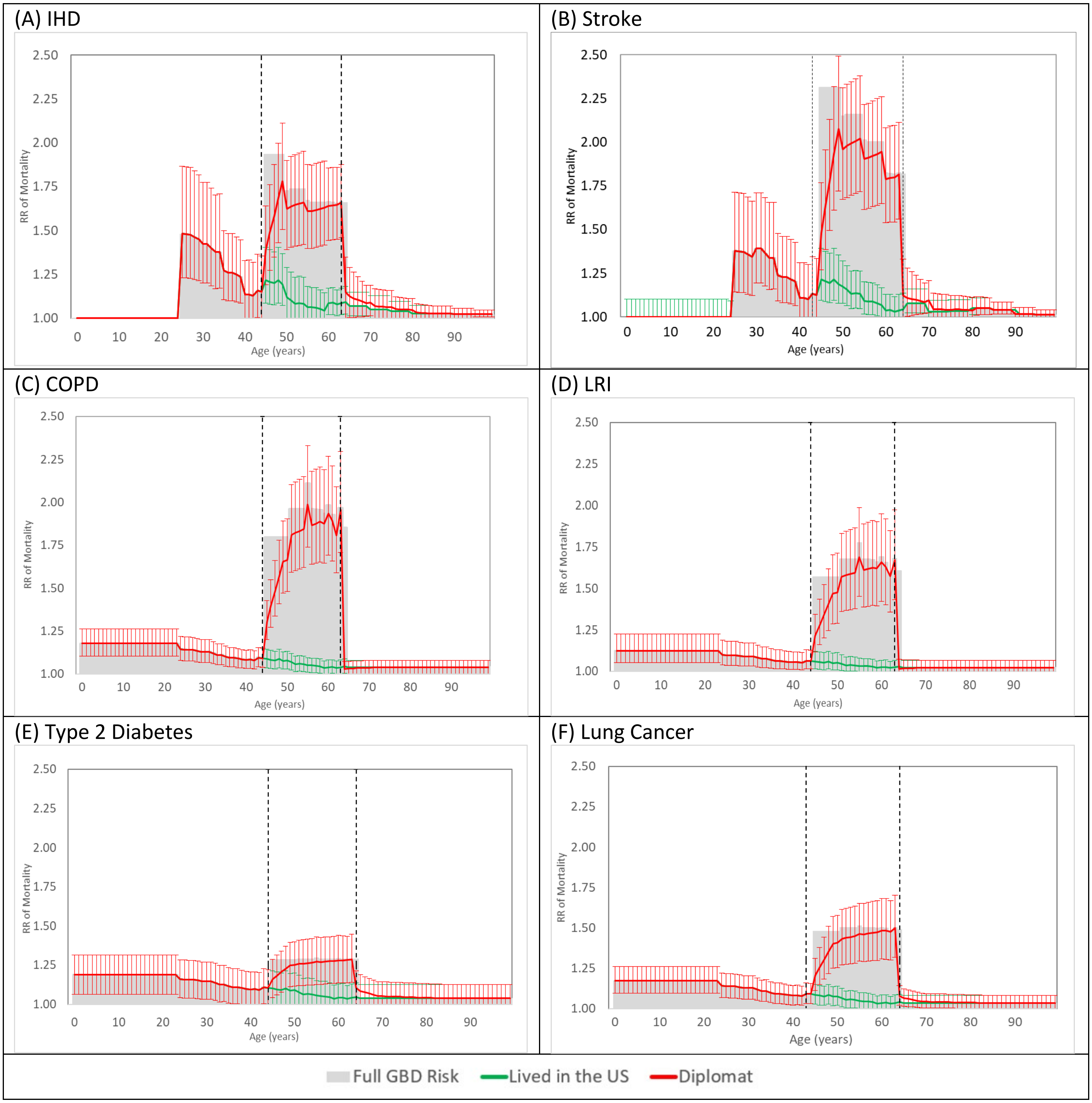


Figure A.26: Assignment 9, older diplomat in "Very high 20 years" assignment; lagged risk relative (RR) of mortality for (A) IHD (B) stroke (C) COPD (D) LRI (E) type 2 diabetes mellitus and (F) lung cancer for a diplomat and the corresponding RR for a person of comparable age living in the US. The beginning and end of the 20 year period with diplomatic assignments is indicated by vertical dashed lines.

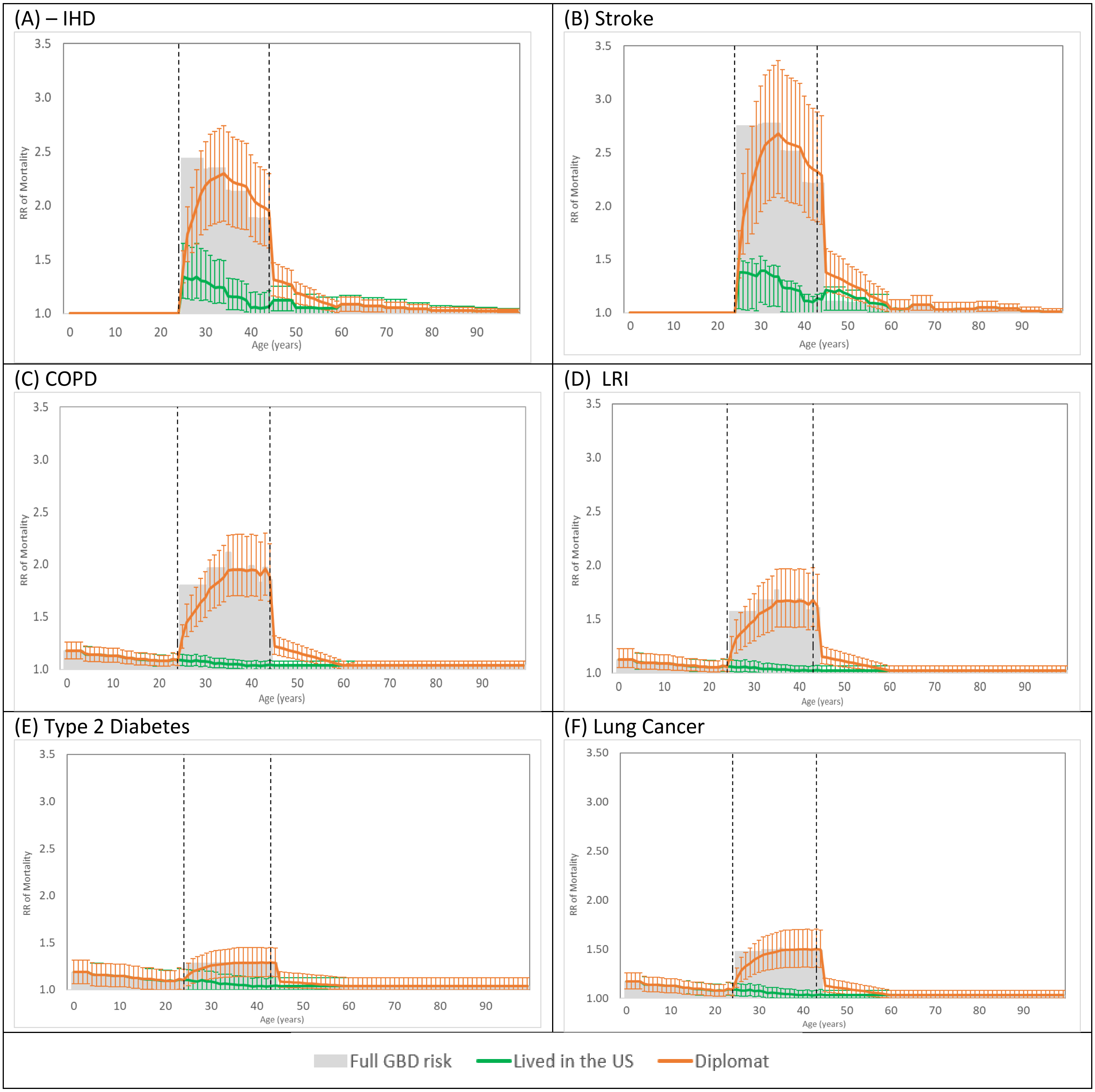


Figure A.27: Assignment 9, young diplomat in "Very high 20 years" assignment; lagged risk relative (RR) of mortality for (A) IHD (B) stroke (C) COPD (D) LRI (E) type 2 diabetes mellitus and (F) lung cancer for a diplomat and the corresponding RR for a person of comparable age living in the US. The beginning and end of the 20 year period with diplomatic assignments is indicated by vertical dashed lines.

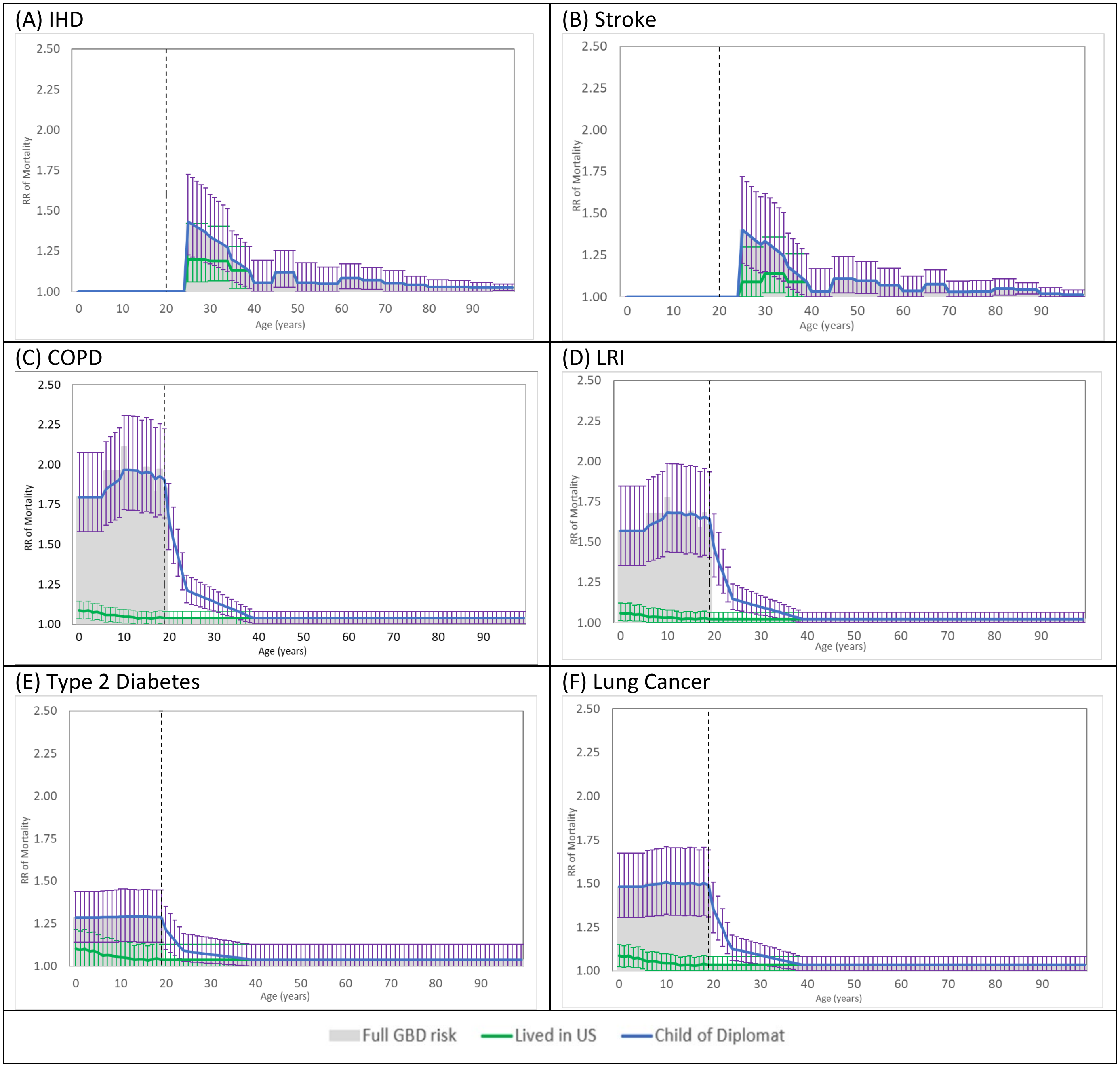
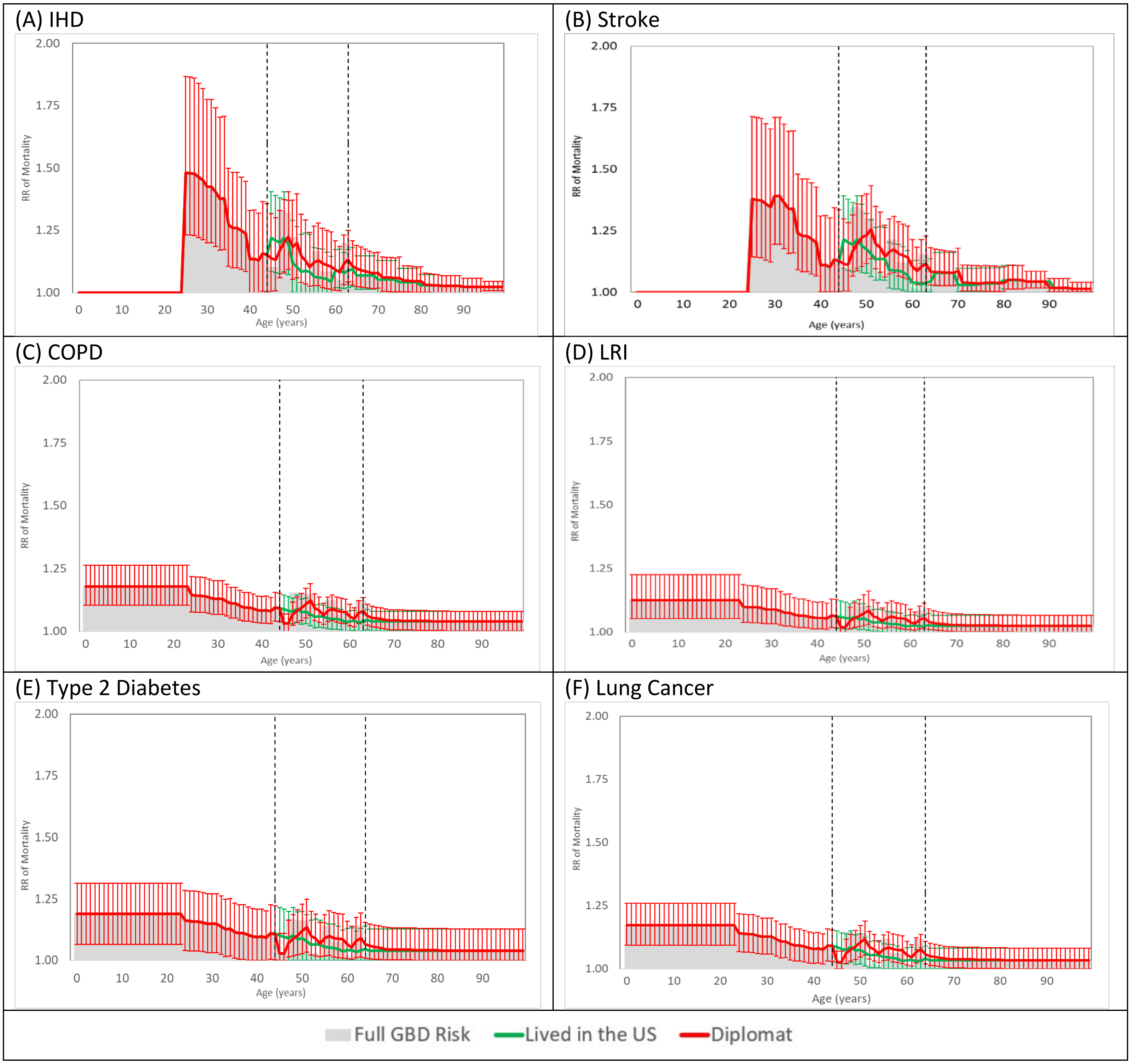


Figure A.28: Assignment 9, child of a diplomat in "Very high 20 years" assignment; lagged risk relative (RR) of mortality for (A) IHD (B) stroke (C) COPD (D) LRI (E) type 2 diabetes mellitus and (F) lung cancer for the child of a diplomat and the corresponding RR for a person of comparable age living in the US. The beginning and end of the 20 year period with diplomatic assignments is indicated by vertical dashed lines.


(A) IHD

(B) Stroke

(C) COPD

(D) LRI

(E) Type 2 Diabetes

(F) Lung Cancer

Figure A.29: Assignment 10, older diplomat in "Standard A with mitigation" assignment; lagged risk relative (RR) of mortality for (A) IHD (B) stroke (C) COPD (D) LRI (E) type 2 diabetes mellitus and (F) lung cancer for a diplomat and the corresponding RR for a person of comparable age living in the US. The beginning and end of the 20 year period with diplomatic assignments is indicated by vertical dashed lines.

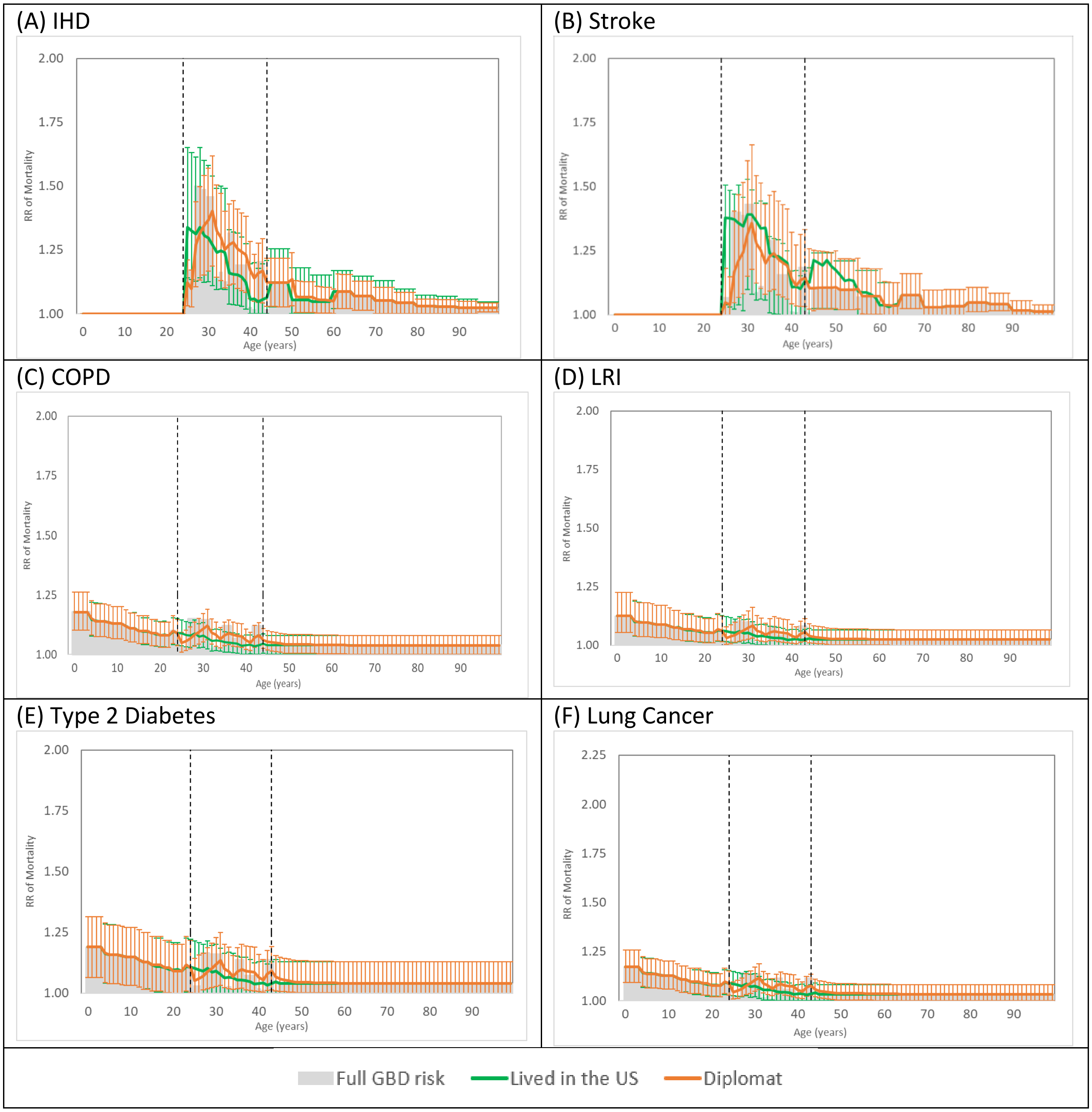


Figure A30: Assignment 10, young diplomat in "Standard A with mitigation" assignment; lagged risk relative (RR) of mortality for (A) IHD (B) stroke (C) COPD (D) LRI (E) type 2 diabetes mellitus and (F) lung cancer for a diplomat and the corresponding RR for a person of comparable age living in the US. The beginning and end of the 20 year period with diplomatic assignments is indicated by vertical dashed lines.

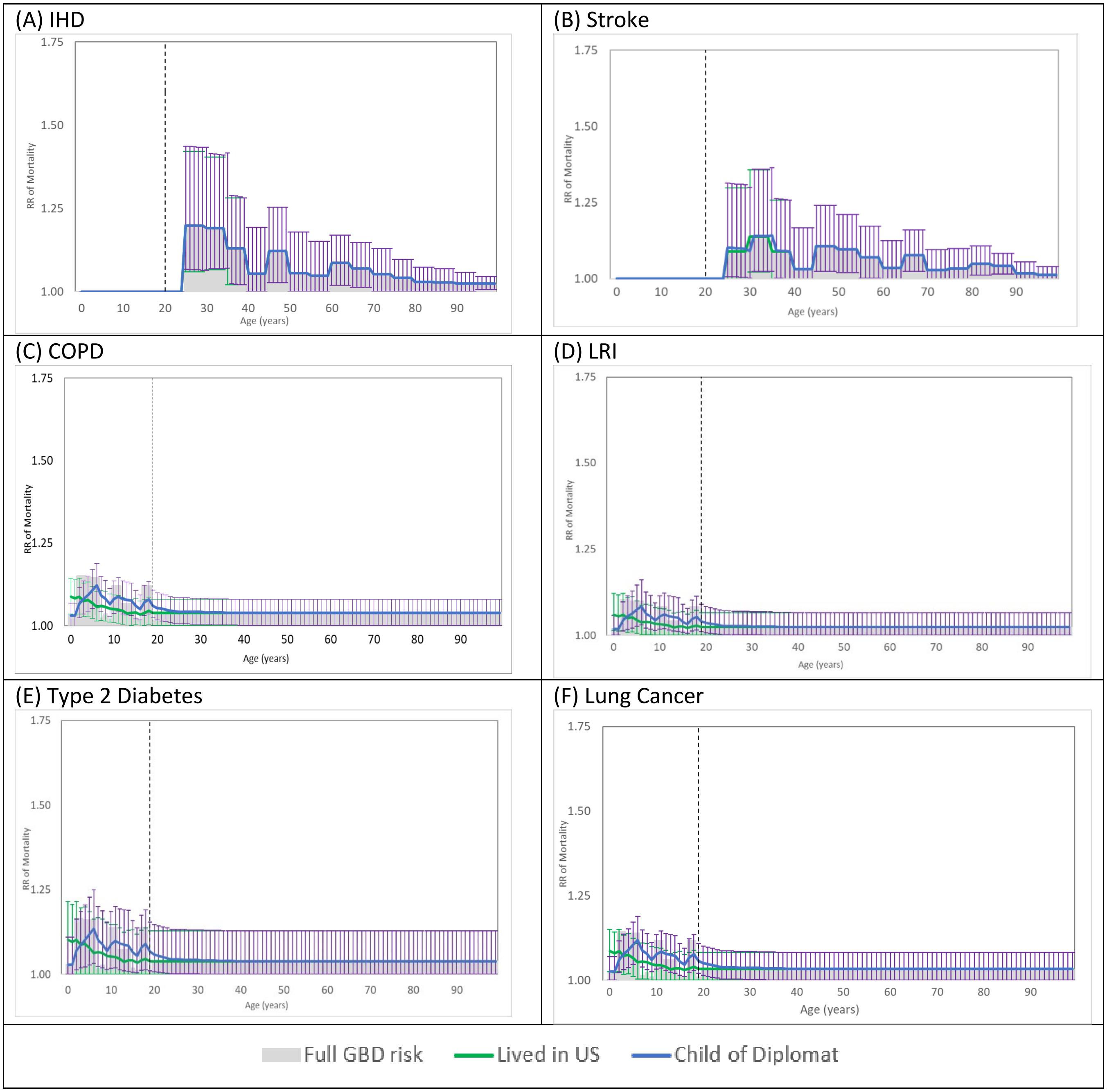


Figure A.31: Assignment 10, child of a diplomat in "Standard A with mitigation" assignment; lagged risk relative (RR) of mortality for (A) IHD (B) stroke (C) COPD (D) LRI (E) type 2 diabetes mellitus and (F) lung cancer for the child of a diplomat and the corresponding RR for a person of comparable age living in the US. The beginning and end of the 20 year period with diplomatic assignments is indicated by vertical dashed lines.