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

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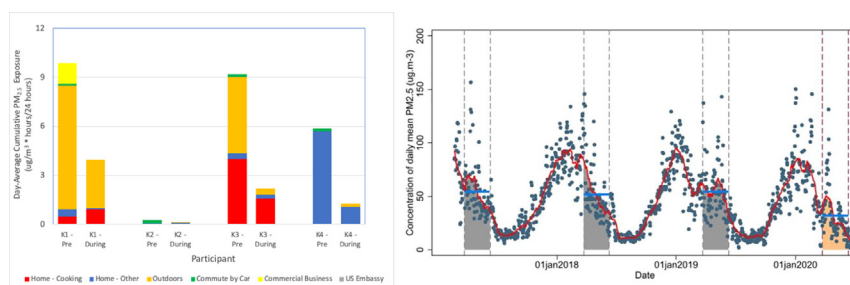
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HIGHLIGHTS

- 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
- 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 INFO

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-19¹) 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

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¹ COVID-19: 2019 Novel Coronavirus SARS-CoV 2, PM_{2.5}: particulate matter with diameter smaller than 2.5 µm; BAM: Beta attenuation monitor, RAC: room air cleaner.

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.

Published by Elsevier B.V.

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; 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 and Ebisu, 2020; Chen et al., 2020; Giani et al., 2020; Kanniah et al., 2020; Kumari and 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, 2020). 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}, PM₁₀, PM₁, 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 co-located 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 ($\mu\text{g}/\text{m}^3 \cdot \text{hours}$) 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 $32.6 \mu\text{g}/\text{m}^3$ (SD $27.7 \mu\text{g}/\text{m}^3$) in 2020 compared with $53.1 \mu\text{g}/\text{m}^3$ (SD $36.1 \mu\text{g}/\text{m}^3$) for 2017–2019 ($p < 0.0001$, Kruskal-Wallis). This represents a reduction of 38.2%. The corresponding figures for Phora Durbar were $33.2 \mu\text{g}/\text{m}^3$ (SD $21.6 \mu\text{g}/\text{m}^3$) in 2020 vs $62.3 \mu\text{g}/\text{m}^3$ (SD $18.8 \mu\text{g}/\text{m}^3$) 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.

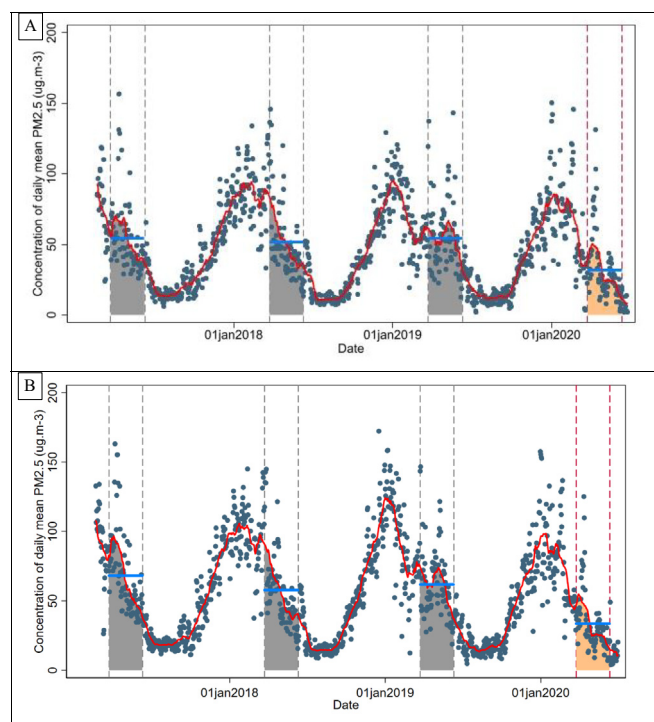


Fig. 1. Monitoring data for ambient $PM_{2.5}$ at [A] the US Embassy and [B] the Phora Durbar Recreational Complex, Kathmandu, 2017–2020. Blue dots represent daily means, the red line is the 31-day moving average and the vertical dashed lines and shading indicate 24 March to 11 June 2020 corresponding 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.

During the lockdown, the mean $PM_{2.5}$ concentration for the period of monitoring for the four study participants ranged from $0.1 \mu\text{g}/\text{m}^3$ (K2) to $3.8 \mu\text{g}/\text{m}^3$ (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 $14.6 \mu\text{g}/\text{m}^3$ (K3) to $22.0 \mu\text{g}/\text{m}^3$ (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 ($0 \mu\text{g}/\text{m}^3$ indoors at the US Embassy and at home when not

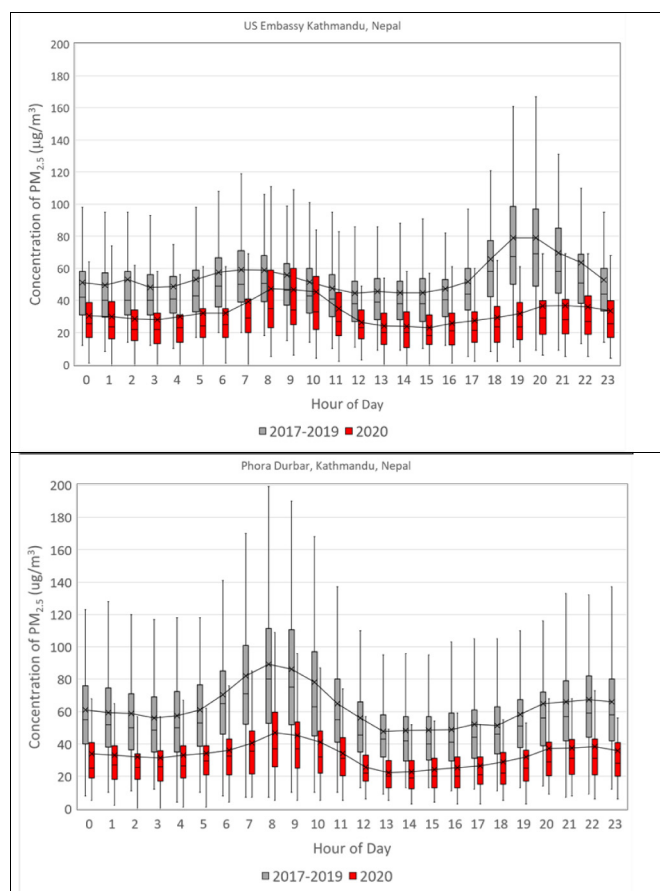


Fig. 2. Diurnal pattern of $PM_{2.5}$ concentrations including mean and interquartile ranges (IQR) at [A] the US Embassy and [B] the Phora Durbar Recreational Complex, Kathmandu, during the period of full COVID-19 restrictions in 2020 (24 March to 11 June, red) and corresponding dates in 2017–2019 (gray).

cooking to $319 \mu\text{g}/\text{m}^3$ at home while cooking) in the concentrations of $PM_{2.5}$ in different microenvironments at different times (Table 1).

Participant K2 had the lowest mean $PM_{2.5}$ concentration at home, excluding time spent cooking – $0.1 \mu\text{g}/\text{m}^3$ 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 (1680ft^2).

K4 had the highest mean $PM_{2.5}$ in the home environment which reduced by from $11.4 \mu\text{g}/\text{m}^3$ prior to the lockdown to $1.5 \mu\text{g}/\text{m}^3$ 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 $2.3 \mu\text{g}/\text{m}^3$, which was 84.2% lower than the mean hourly ambient $PM_{2.5}$ concentration measured at the US Embassy's fixed site monitor of $14.6 \mu\text{g}/\text{m}^3$ (Table 1). The tracing for this day, 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

Table 1

Mean concentration of $PM_{2.5}$ by microenvironment for participants K1, K2, K3 and K4 and daily mean $PM_{2.5}$ measured at fixed-site outdoor monitor^a for the corresponding days.

		Mean [$PM_{2.5}$] in $\mu\text{g}/\text{m}^3$											
		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 ^a for days of personal monitoring		40.9 (34, 44)	22.0 (14, 27)	–46%	45.1 (37, 54)	16.8 (14, 21)	–63%	70.9 (49, 92)	14.6 (8, 21)	–79%	15.8 (12, 20)	17.6 (14, 23)	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%

Note: all data related to weekday monitoring.

^a Embassy fixed-site monitor.

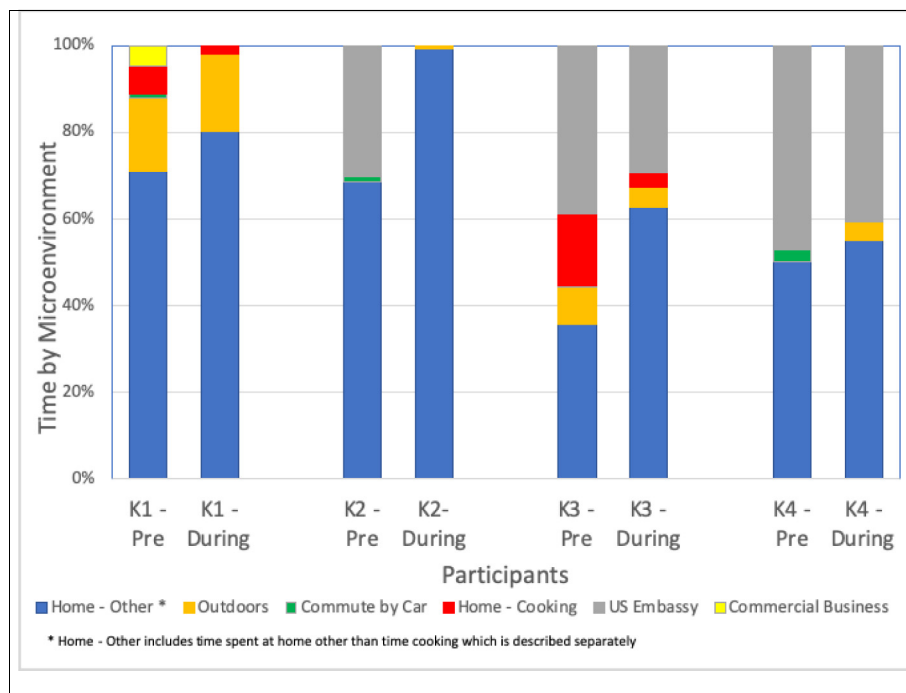


Fig. 3. Comparison of time-activity patterns (time in specified microenvironments) before (pre) and during the period of full COVID-19 restrictions (24 March to 11 June 2020).

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.

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 (Rodríguez-Urrego and Rodríguez-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 et al., 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

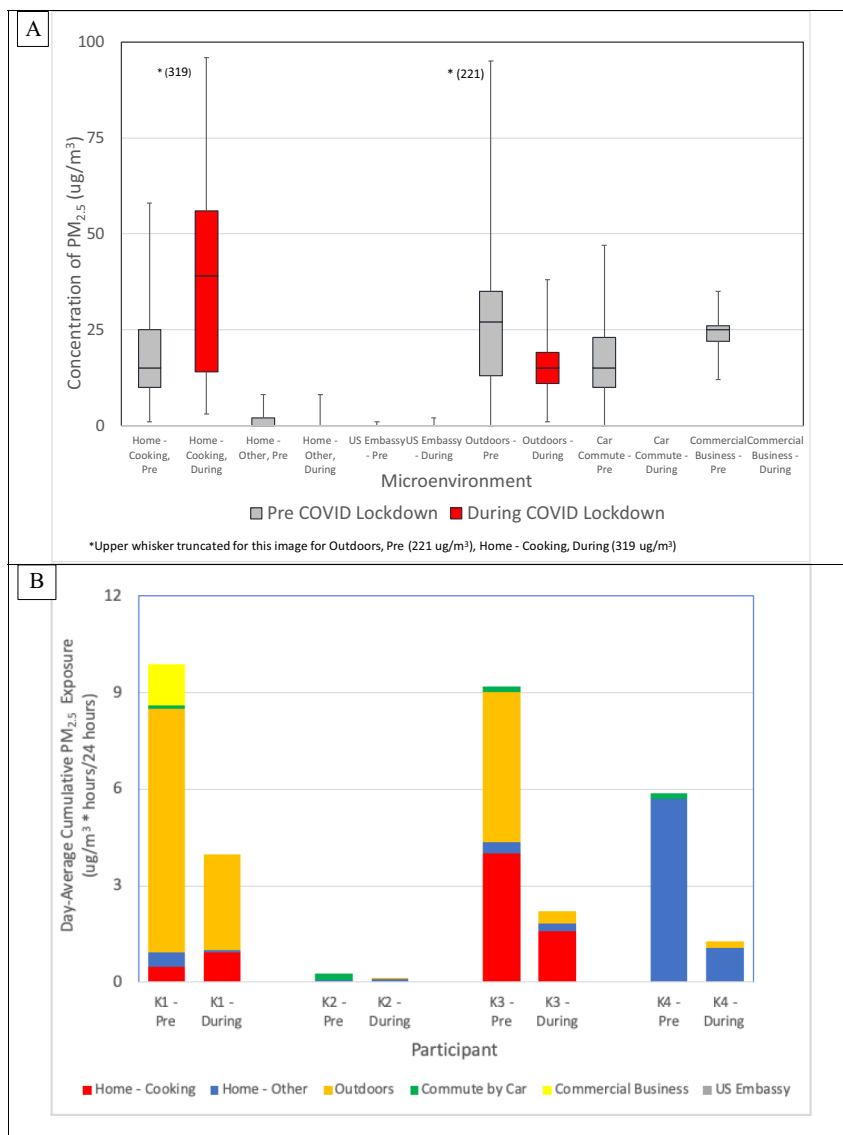


Fig. 4. [A] Median, minimum, maximum and interquartile range (IQR) concentrations of PM_{2.5} by microenvironment and [B] contribution of each microenvironment to the day-average cumulative exposure computed as the product of PM_{2.5} concentration and hours of exposure per day (µg/m⁻³·h). Both graphs 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-%)

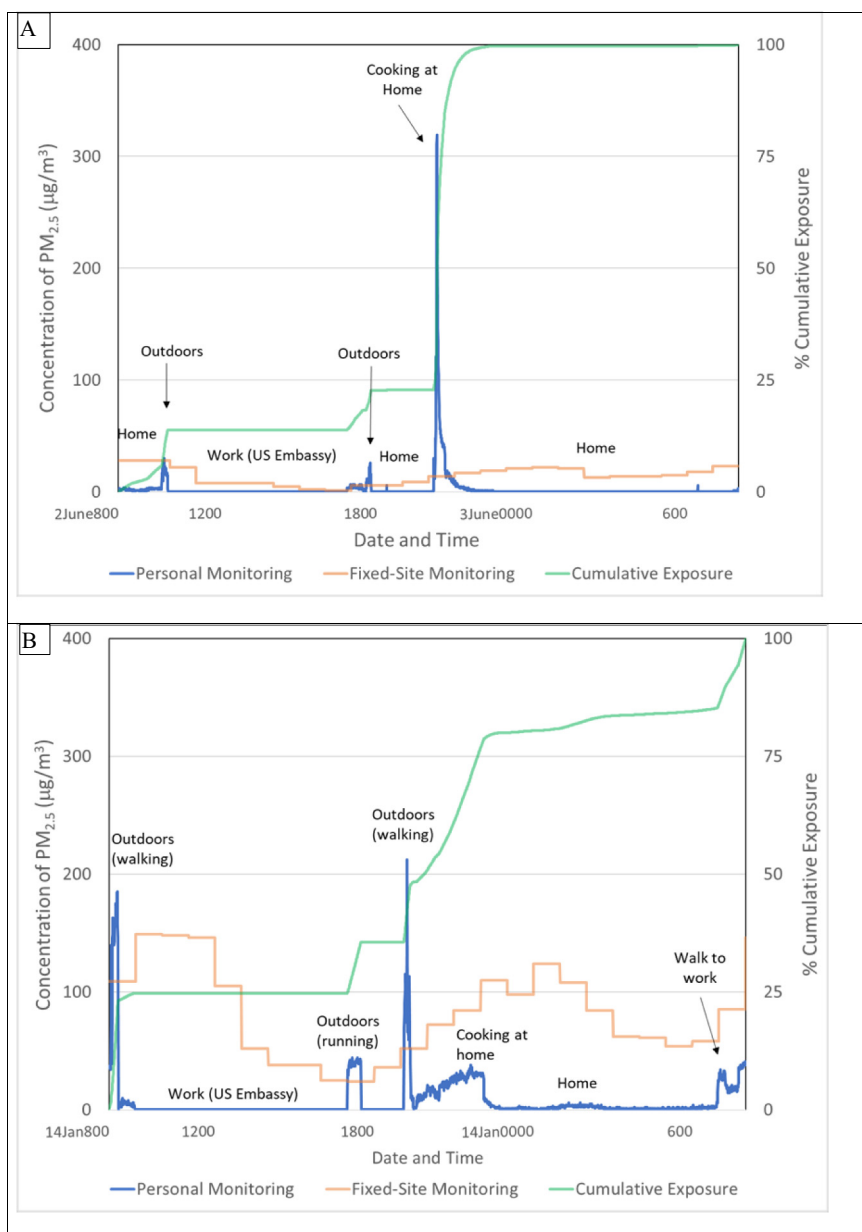


Fig. 5. [A] Personal exposure profile for participant and time activity pattern for an example day during and [B] before full COVID-19 restrictions. Data for volunteer K3.

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>.

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