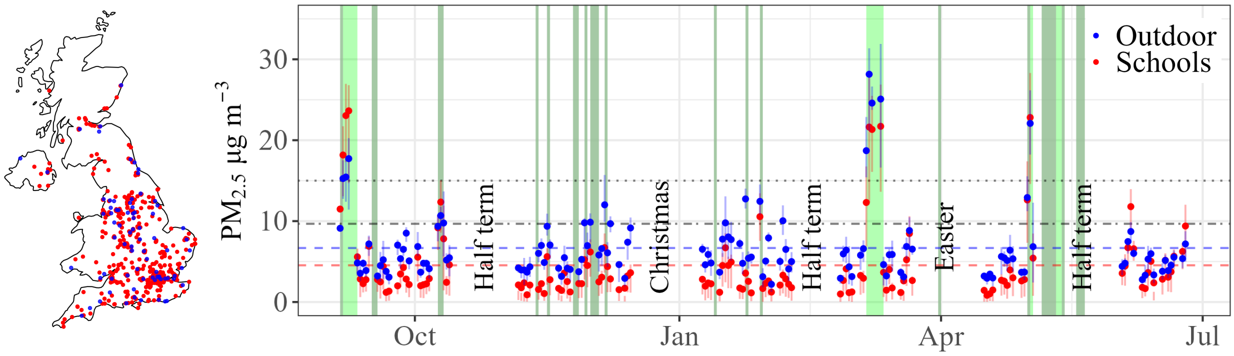
# Graphical Abstract

**Particulate matter $PM_{2.5}$ concentrations in UK schools: a nationwide study into the influence of ambient $PM_{2.5}$ and the resulting exposure potentials**

Alice E. E. Handy, Samuel G. A. Wood, Katherine Roberts, Christopher S. Malley, Henry C. Burridge, The SAMHE Project Consortium



# Highlights

**Particulate matter $PM_{2.5}$ concentrations in UK schools: a nationwide study into the influence of ambient $PM_{2.5}$ and the resulting exposure potentials**

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- Concentrations of $PM_{2.5}$ were monitored in 490 schools across the UK during the academic year 2023–2024.
- School $PM_{2.5}$ concentrations closely correlated to ambient outdoor $PM_{2.5}$ concentrations.
- Outdoor air is a key source of $PM_{2.5}$ in the schools monitored.
- Outdoor $PM_{2.5}$ events — periods of elevated outdoor $PM_{2.5}$ concentration — lead to high concentrations in schools.
- The potential dose of $PM_{2.5}$ received during these $PM_{2.5}$ events is estimated to contribute significantly to the potential total dose over the academic year.

# Particulate matter $PM_{2.5}$ concentrations in UK schools: a nationwide study into the influence of ambient $PM_{2.5}$ and the resulting exposure potentials

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**Abstract**

This paper analyses the concentration of particulate matter $PM_{2.5}$ from monitors deployed, by the Schools' Air Quality Monitoring for Health and Education Initiative (SAMHE), to 490 schools across the United Kingdom throughout the academic year 2023—2024. The data shows that the $PM_{2.5}$ concentration in schools is closely correlated to the ambient outdoor $PM_{2.5}$ concentrations. Whilst the evidence gathered indicates that sources of $PM_{2.5}$ within schools contribute to the concentrations, it is shown that outdoor sources are the dominant signature within the $PM_{2.5}$ concentration measurements made indoors. Moreover, over the academic year, outdoor $PM_{2.5}$ events — periods of elevated outdoor $PM_{2.5}$ concentration — are shown to account for approximately 41% of the total potential dose, whilst occurring on only around 13% of schooldays. These, and other findings presented herein, have important implications for school air quality and how air quality within schools, and beyond, is managed.

*Keywords:* Particulate Matter, $PM_{2.5}$, Schools' Air Quality, Exposure, UK, Indoor, Outdoor

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## 1. Introduction

The detrimental effects of particulate matter (PM) on health are well documented and are linked to adverse respiratory and cardiovascular health effects (Kim et al., 2015). Particular attention is given to the harmful effects of particulate matter with an aerodynamic diameter less than 2.5 $\mu$m ($PM_{2.5}$) as these fine particles can penetrate deeper into the lung, with a proportion of ultrafine particles ($PM_{0.1}$) crossing over into the bloodstream to reach other organs (Exley et al., 2022). Children are more vulnerable to the detrimental effects of $PM_{2.5}$ as they breathe in a larger amount of air per unit body mass compared to adults, which can have damaging effects on their developing immune systems and lungs (Rees, 2017). Long-term exposure to $PM_{2.5}$ is associated with negative effects on lung development and with the exacerbation of asthma in children (Son, 2023; Exley et al., 2022). This can result in increased school absenteeism, an increased need for doctor visits, hospitalisation and is detrimental to children's well-being (Zhang et al., 2022). Beyond the consequences on children's health, poor air quality is linked to a reduction in cognitive performance which can have negative consequences for pupil attainment (Wargocki et al., 2020; Sadrizadeh et al., 2022).

School buildings are a key environment for children where they spend approximately 30% of their time (Son, 2023; Faria et al., 2020). It is therefore essential to measure and understand the concentrations of $PM_{2.5}$ in schools. Clearly, providing a safe and healthy environment for children is essential, and whilst there are no guidelines specific to particulate matter in UK schools, the World Health Organisation recommends that, on health-based grounds, the 24-hour mean concentration of $PM_{2.5}$ of both indoor and outdoor air should not exceed 15 $\mu g/m^3$ (WHO, 2021).

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Particulate matter in schools can originate from indoor sources or outdoor sources brought inside through openings in the building fabric (e.g. windows and doors) — it is an aim of this study to contribute findings on the relative importance of indoor and outdoor sources for the $PM_{2.5}$ concentrations measured in schools. Many studies have shown that school occupants, resuspension of settled dust, and outdoor air are significant contributing sources of particulate matter in school classrooms (Amato et al., 2014; Faria et al., 2020; Becerra et al., 2020). For example, Amato et al. (2014) collected $PM_{2.5}$ samples from indoor and outdoor environments of 39 primary schools and found 47% of indoor samples to have originated from indoor sources (including skin flakes, clothes fibres, VOC's, and the resuspension of soil particles) and the remaining 53% of indoor sources to have infiltrated into the classroom from outdoors. The indoor-outdoor ratio of particulate matter within schools can vary significantly depending on building design, building operation, ventilation, and the intensity of outdoor pollution sources (Poupard et al., 2005; Stamp et al., 2022; Mohammadyan et al., 2017). Particulate matter in the outdoor air that surrounds school buildings can originate from sources generated locally (such as roadside traffic pollution and road dust), as well as regional sources like industrial emissions, and even trans-boundary sources (Mohammadyan et al., 2017; Harrison et al., 2012).

Studies that have investigated $PM_{2.5}$ in schools predominantly consider cohorts of schools within a specific urban setting or region, are often limited in the number of schools they include, and are short-term in their nature. It is therefore challenging to extrapolate findings to implications for the national school stock (in the UK approximately 23 000 schools). The SAMHE method allows for longitudinal monitoring of $PM_{2.5}$ concentrations, amongst other indoor air quality (IAQ) metrics, in schools across the UK. As of September 2024, over 1 300 schools have been recruited to SAMHE and 880 of the monitors within schools had recorded IAQ data in schools. In this paper, we consider a national dataset of concentration of $PM_{2.5}$ in 490 schools at locations across the UK over the academic year 2023—2024.

This paper investigates the temporal trends in school $PM_{2.5}$ concentrations across an entire academic year. Attention is given not only to the long-term impact of $PM_{2.5}$ in schools through evaluation of a 'potential dose', but also to episodes of elevated PM concentration, or '$PM_{2.5}$ events', which can have pertinent consequences for acute health. The remainder of this paper is structured as follows. The details of the SAMHE methodology which facilitates the collection of a large longitudinal dataset is outlined in §2.1. The formation of the $PM_{2.5}$ concentration datasets analysed in this paper is described in §2.2 and §2.3 for the SAMHE schools and outdoor $PM_{2.5}$ concentration respectively. In §3, the results of this study are presented, beginning with examining the $PM_{2.5}$ concentration trends over the academic year in §3.1. The impact of 'outdoor $PM_{2.5}$ events' on the concentration in schools is then evaluated in §3.2, and in §3.3 it is shown that these events contribute significantly to the total potential dose of $PM_{2.5}$ received at school over the academic year. Finally, in §4 conclusions are drawn.

## 2. Methods

### *2.1. SAMHE methodology*

This paper analyses indoor air quality data from within the 490 UK schools that sent data, meeting data completeness criteria (see below), as part of the SAMHE project during the academic year 2023-2024, herein 05/Sep/23–25/Jun/24. Through a standardised method (documented by Chatzidiakou et al., 2023; West et al., 2023) the SAMHE project, as part of the SAMHE initiative, has begun gathering a longitudinal dataset of indoor air quality in school throughout the UK. During the recruitment phase of the project (May 2023 to May 2024) any UK school (providing education to pupils aged above four years old) could apply to participate in SAMHE. Recruitment efforts were made to ensure that participating schools represented the UK school population in certain key demographics, including fee-paying versus state-funded schools, their constituent country within the UK, and Index of Multiple Deprivation (IMD, which ranks areas based on several metrics of relative deprivation). Once a school was accepted as a SAMHE school, they were sent a free WiFi-enabled low-cost air quality monitor and provided with instructions on how to connect it to their school's internet network and where to place the monitor within classrooms. Each school was also provided with ongoing access to a Web-App, where the air quality data recorded by their SAMHE monitor can be visualised and, through which, tailor-made curriculum-linked resources made available. By August

2024, there were over 1 300 SAMHE schools, of which 28 are schools (354 monitors combined) are part of an HEPA filter intervention study and have received more than one monitor, all other SAMHE schools have a single monitor. Only those SAMHE schools which were not part of the HEPA intervention study were considered in this study. During the study period, SAMHE monitors record readings every minute of: $CO_2$, relative humidity, total volatile organic compounds, temperature, and particulate matter; the last of which is ultimately measured via a 'Plantower PMS5003' sensor (which employees a laser scattering principle) — these $PM_{2.5}$ measurements form the focus of this study.

*2.2. SAMHE dataset in this study*

This study analyses a subset of all the concentrations of $PM_{2.5}$ recorded by SAMHE schools' monitors, over the period from the start of the Autumn term 2023 to the end of Summer term 2024. We consider the school-year to start on the first day that all UK schools are expected to be 'in term' during the autumn of 2023 and finish on the last day that all UK schools are expected to be 'in term' during the summer 2024. Within this period we define non-schooldays to included: weekends, any days on which schools within the four nations of the UK are out of term-time and on 'school holidays', and any days with are local or national holidays within any UK nation. As such, on any schoolday all SAMHE schools are expected to be active (i.e. have pupils in attendance). The dates on which SAMHE schools are deemed to be 'in term' are summarised, by each 'half-term', in table A.1.

We consider two periods of time and, for each, two associated datasets. First, we describe the 24-hour period every day (including non-schooldays, e.g. weekends, etc.) from the start of the Autumn term 2023 to end of Summer term 2024 as the "continuous period" — a period of 295 days in total — and the analysis of the $PM_{2.5}$ concentrations throughout this period as being analysis of the "continuous period dataset". Second, the "school-year" describes only every schoolday and only between the hours of 09:00 and 16:00 — 133 days in total — and the analysis of the $PM_{2.5}$ concentrations throughout the school year being the analysis of the "schoolday dataset".

On each day of the continuous period, data is only included from schools that report minutely $PM_{2.5}$ concentrations for more than 75% of the 24-hours, i.e. for more than 1 080 minutes. During the academic year 2023–2024, the SAMHE project recruited an increasing number of schools. As a consequence, the number of schools from which data can be included within this study increased throughout the year. On all days, and for each school, a mean over the full 24-hour period is calculated; the average of these values over the included schools are described as the "SAMHE 24-hour mean $PM_{2.5}$ concentration", providing a dataset of 295 values. The minimum number of schools reporting data that met the inclusion criteria on any day within the continuous period dataset was 123 and the maximum was 339; as such, the 'SAMHE 24-hour mean $PM_{2.5}$ concentrations' reported herein for each day always reflect averages across between 123 and 339 schools.

The 'schoolday dataset' is formed by, on each schoolday, selecting only the schools that report $PM_{2.5}$ concentrations for more than 75% of the time during the school day, i.e. for more than 315 minutes between 09:00 and 16:00. On all schooldays, and for each school, a mean over the duration between 09:00 and 16:00 is calculated; the average of these values over the included schools are described as the "SAMHE schoolday mean $PM_{2.5}$ concentration", providing a dataset of 133 values. It is natural that, on a given day, there are more schools that meet the data completeness criteria during the 7 hours of the schoolday period than those meeting the data completeness criteria over the 24-hour period. For the schoolday dataset, the minimum number of included schools on any schoolday was 136 and maximum was 346; as such, the 'SAMHE schoolday mean $PM_{2.5}$ concentrations' reported herein for each day always reflect averages across between 136 schools and 346 schools.

In total over the year, this study reports on data gathered from within 490 schools across the UK (see figure 1 for an illustration of their locations). Herein, the analysis will be evaluating the 24-hour mean $PM_{2.5}$ concentrations and schoolday mean $PM_{2.5}$ concentrations — as shown in Appendix B, the probability density distributions of concentrations are largely unchanged between the primary datasets reported in §3 (i.e. taking 1-day means) and either examining the minutely data or taking hourly means.

The extent to which the results of this study are sensitive to the data completeness criteria, and the construction of the datasets analysed, is evaluated by comparing the results based on analysis of the primary datasets (presented in §3) to those that would be deduced should alternate datasets, resulting from a different construction, be analysed. The alternate datasets are constructed by, in addition to the above completeness criteria, insisting that each included school also meets these inclusion criteria on more than 75% of schooldays within the school-year (i.e. on more than 99 schooldays). Hence, whilst the population of schools included within the primary datasets can evolve as schools join SAMHE and schools' monitors become connected, disconnected, or reconnected, the population of included schools within the alternate datasets remains fixed over the entire academic year. Comparing summary statistics of the primary and alternate datasets, see Appendix C, illustrates that the findings and conclusions of this study remain unchanged irrespective of the choice of dataset construction made.

### *2.3. Other datasets*

The SAMHE $PM_{2.5}$ concentration datasets are compared in §3 to datasets constructed from measurements of ambient outdoor $PM_{2.5}$ concentrations based on those reported by Defra AURN monitoring sites, and only those recorded at sites being representative of ambient 'background' levels. These concentrations of $PM_{2.5}$ are reported at hourly intervals by the AURN sites, and we identify the nearest background AURN site to each included SAMHE school — only data from these sites are used in the analysis presented. We constrain our analysis to 'background' AURN sites which are intended to be the sites positioned so that the pollution data recorded is representative of several square kilometres and not influenced by any single local source of pollution (see Defra AURN, 2024). Industrial and traffic sites are omitted since these are positioned to capture the effects of pollution due to specific industrial activities or nearby traffic which, it is expected, is less representative of the outdoor air quality surrounding SAHME school buildings.

The number of AURN sites from which data is selected can vary each day depending on the SAMHE schools included in the datasets on that day, and is further effected by the completeness of data reported by AURN sites. An equivalent data completeness criteria was applied to the data from AURN sites to that of the SAMHE schools. That is, for the continuous period, on each day only sites that reported concentrations of $PM_{2.5}$ data for more than 75% of the 24-hours were included. On each day, out of these sites, the AURN site nearest to each included school (included within the 'continuous period SAMHE dataset' on that day) is selected — based upon the geographical distance — with some AURN sites being the nearest to many schools. The analysis of the "continuous period AURN dataset" describes the analysis of the 295 "AURN 24-hour mean $PM_{2.5}$ concentrations" which are calculated for each day within the continuous period as the average of the 24-hour mean $PM_{2.5}$ concentrations from each included AURN site, on each day. Over the continuous period, the minimum number of AURN sites from which data is included, on any given day, to calculate the 'AURN 24-hour mean $PM_{2.5}$ concentration' is 49, and maximum is 66. The mean of the distances between each school and the nearest AURN site varies each day between 14.2 km and 18.3 km.

Similarly, to form the "school-year AURN dataset", only AURN sites that report data for more than 75% of a given schoolday, between the duration 09:00-16:00, are included for that day. Each schoolday, from these sites, the nearest site to each included school in the school-year SAMHE dataset is found. Then, for each AURN site, a mean $PM_{2.5}$ concentration over each schoolday (between 09:00 and 16:00) is calculated, these values, averaged across all included sites are described as the "AURN schoolday mean $PM_{2.5}$ concentrations" — providing another dataset of 133 values. The minimum number of AURN sites included in the 'school-year AURN dataset', on any given day, is 50, and the maximum is 67. The mean of the distances between each school and the nearest AURN site varies each schoolday between 14.8 km and 19.2 km. Over the year, data from 77 AURN sites in total were used in this study, the locations of these are shown in figure 1.

As will be revealed in §3, high concentrations of $PM_{2.5}$ were recorded in SAMHE schools when the outdoor concentration measurements were elevated — to aid analysis we categorise periods of elevated outdoor $PM_{2.5}$ concentrations as '$PM_{2.5}$ events'. Two sets of outdoor $PM_{2.5}$ events are defined as any day, or set of consecutive days, when the AURN 24-hour mean $PM_{2.5}$ concentration exceeds a threshold value of $15\,\mu g/m^3$ (as per WHO guidance (WHO, 2021)), or a threshold defined as the median plus one standard deviation of the measured data (see §3.2).

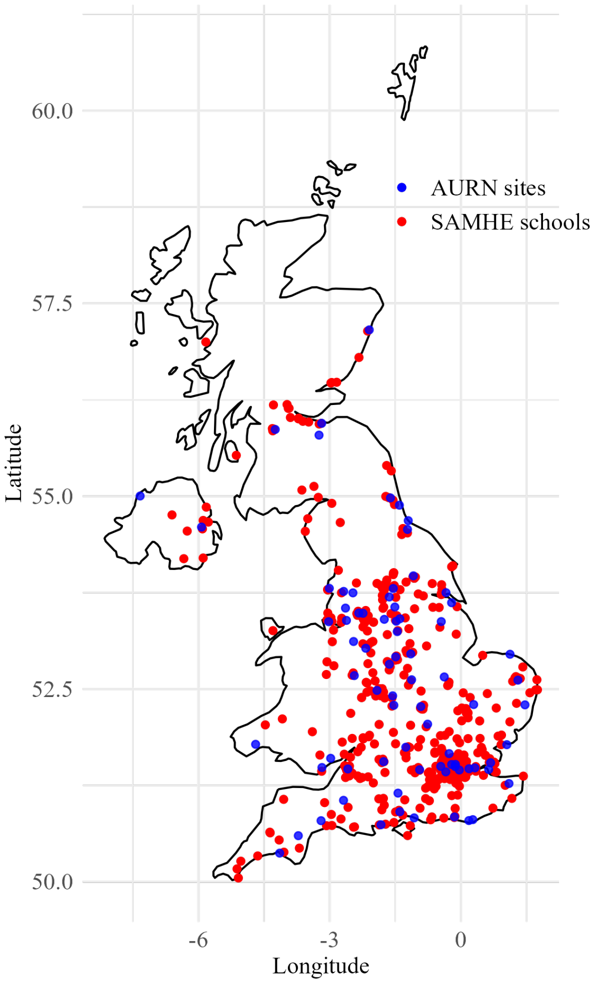



Figure 1: Map outlining the UK (i.e. Great Britain and Northern Ireland), showing the location of the schools from which data is included in the reported analysis, and the location of the background AURN sites used within the analysis (that are those nearest to the schools).

## 3. Results

Over the academic year the SAMHE $PM_{2.5}$ concentrations vary considerably, see figure fig:PMvsTime. Moreover, there is often a larger variation in SAMHE $PM_{2.5}$ concentrations per day than between schools, as shown in figures 2a and 2b by a greater difference between values of the red circular markers than the height of the vertical red bars which show the interquartile range of daily-mean values measured across included SAMHE schools. The SAMHE $PM_{2.5}$ concentration when considering just the period that schools are occupied (between 09:00-16:00 on schooldays) is typically higher than the SAMHE 24-hour mean $PM_{2.5}$ concentrations on a given day. Over the entire year, the mean of the SAMHE schoolday dataset, i.e. the mean of the 133 values of SAMHE schoolday mean $PM_{2.5}$ concentrations, is $4.54\,\mu g/m^3$. This is higher than the associated mean of the continuous period dataset, i.e. the mean of the 295 SAMHE 24-hour $PM_{2.5}$ concentrations, of $3.71\,\mu g/m^3$. These mean values are indicated by the red dashed lines in figures 2a and 2b, and the mean, median and standard deviation of both the continuous period and schoolday datasets are given in the first row of table B.1. It is, however, worth noting that the mean measurements are both small compared to the extreme variations; for example, for both the continuous period and schoolday datasets the differences between the maximum and minimum of the daily values obtained are over $20\,\mu g/m^3$. The indoor-outdoor ratio, as shown in figure 2c, is typically less than unity in value, however, is also highly variable. When comparing the continuous period dataset, i.e. ratios associated with 24-hour means shown by grey markers, to the schoolday dataset, the ratios associated with on the 09:00-16:00 means only on schooldays shown by purple markers, the ratio is typically higher for the schoolday dataset.

We note that the mean $PM_{2.5}$ concentrations measured in SAMHE schools over the year are within the range of some studies published in the literature, and lower than others (e.g. Hama et al., 2023; European Commission et al., 2014). A systematic review (Son, 2023) has shown that concentrations in classrooms varied widely, and varied between nations — they did not include UK schools, but we note that from the studies they did review from within 8 nations, the concentrations were reported in the range of 8–$100\,\mu g/m^3$. Furthermore, some of the studies reviewed therein selected schools which were deliberately near to a particular pollution source; for example, the study that reported the highest value ($100\,\mu g/m^3$), investigated the impact of the school's wood-burning heating system on air quality. None of these studies continually monitored any schools for an entire academic year, most frequently sampling for a period of one to two weeks. These studies we conducted as early as 1997 and as recently as 2013. We note that the annual mean ambient outdoor concentration of $PM_{2.5}$ fell by $4.8\,\mu g/m^3$ between 2013 and 2023 in the UK (DEFRA, 2024) with similar reductions in Europe (EEA, 2013, 2024). Nevertheless, we note that most studies reviewed therein deployed gravimetric sampling whilst the $PM_{2.5}$ sensors for SAMHE monitors use a laser scattering principle (see §2.1). Crucially, the primary focus of the present study is the relative changes in concentration due to the changes in outdoor concentration; in what follows, the data gather by the SAMHE monitors is compared to (outdoor) measurements from reference grade measurement stations installed and maintained by the UK government — the comparison shows reassuring patterns and reasonable values for indoor-outdoor ratios.

To contextualise the large variation in $PM_{2.5}$ concentrations measured in SAMHE schools, we next analyse them alongside the $PM_{2.5}$ concentrations of ambient outdoor air as measured at AURN sites (§3.1). The effect of periods of high outdoor $PM_{2.5}$ concentrations, or 'outdoor $PM_{2.5}$ events', on school $PM_{2.5}$ concentrations are examined in greater detail in §3.2. Finally, in §3.3, a gauge of the accumulated effect of varying $PM_{2.5}$ concentrations over the academic year is assessed by estimating the dose received. The contribution that potential exposure during events had to the total does is also assessed.

### *3.1. Analysis of the SAMHE school and AURN outdoor $PM_{2.5}$ concentrations over the academic year*

Across the academic year 2023—2024, the SAMHE $PM_{2.5}$ concentrations, measured by the SAMHE schools' monitors, are well correlated with the AURN $PM_{2.5}$ concentration measurements from outdoors. By comparing the 'schoolday datasets' so that only periods when the schools were operational (and their buildings expected to be occupied and actively ventilated), i.e. the SAMHE and the AURN schoolday mean $PM_{2.5}$ concentrations are significantly correlated (illustrated in figure 2b), with a Spearman's rank correlation coefficient of approximately 0.77, with a p-value of $p < 2.2 \times 10^{-16}$ — we note that the school

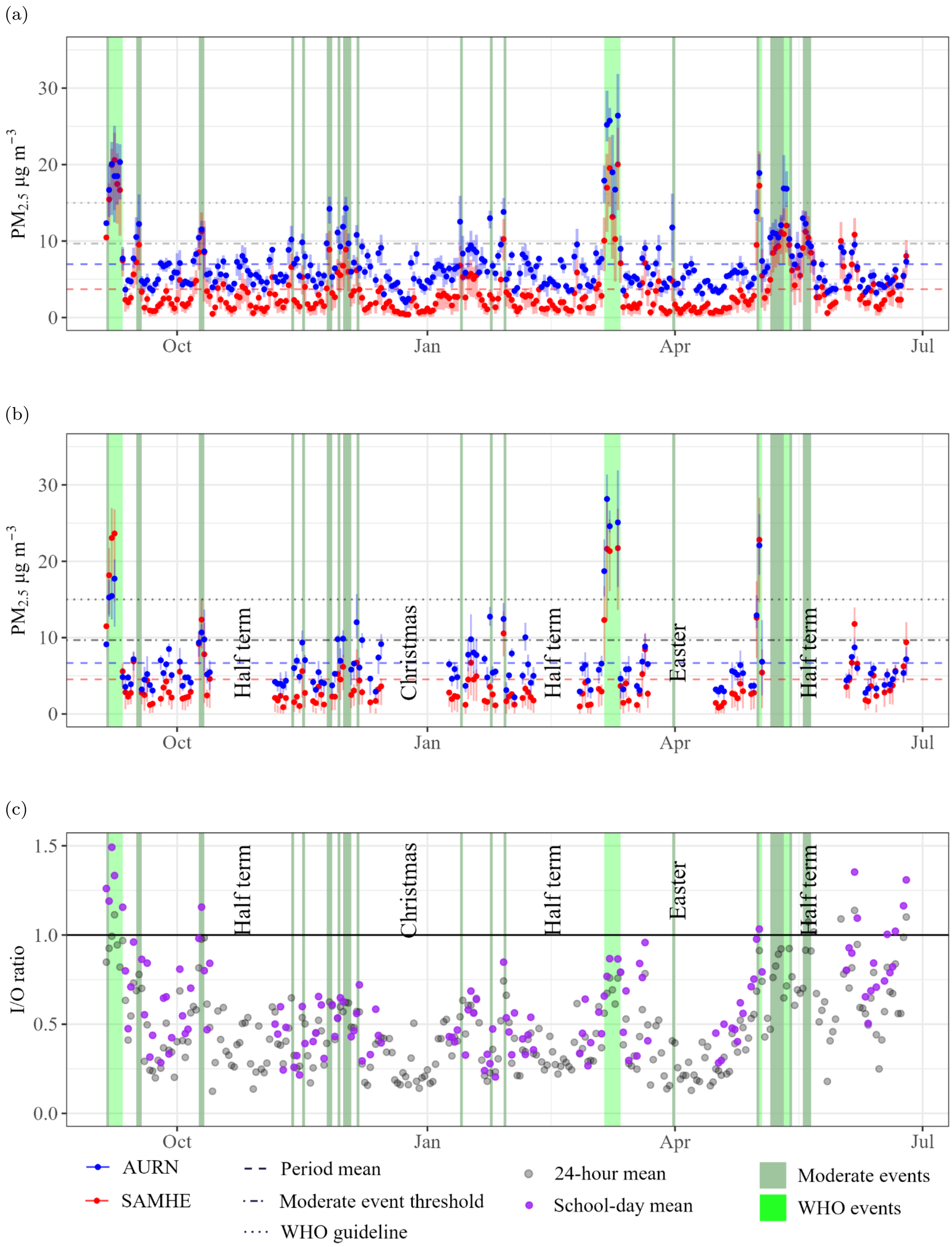



Figure 2: Time series illustrating the variation in $PM_{2.5}$ concentrations throughout the academic year 2023–2024 as measured by the SAMHE monitors in schools, and the AURN sites outdoors. Within (a), red circular markers indicate the average of, and the vertical bars indicate the interquartile range within, the 24-hour mean $PM_{2.5}$ concentration measurements across SAMHE schools' on each calendar day; blue circular markers and the vertical bars indicate the equivalent data from the AURN sites' measurements of ambient outdoor concentrations. Within (b), red circular markers indicate the average of, and the vertical bars indicate the interquartile range within, the schoolday mean $PM_{2.5}$ concentration measurements across SAMHE schools' on each schoolday; blue circular markers and the vertical bars indicate the equivalent from the AURN measurements outdoors. Within (c) the 'Indoor-outdoor ratio' of, appropriately averaged, school-outdoor concentrations: grey markers indicate the ratios based on the 24-hour mean $PM_{2.5}$ concentration measurements on each calendar day (i.e. the circular markers plotted in (a)), and purple markers indicate the ratios based on the schoolday mean $PM_{2.5}$ concentration measurements on each schoolday (i.e. the circular markers plotted in (b)). In each pane, the green vertical panels show periods when '$PM_{2.5}$ events' occur, light green showing $PM_{2.5}$ events for which the outdoor concentration exceeded the WHO guideline and dark green for moderate $PM_{2.5}$ events.

and AURN measurements were not co-located and were separated by a mean distance of between 14 km and 20 km. Moreover, we note that the strong correlation is evident despite the many potential sources of $PM_{2.5}$ in school air, including numerous sources from schools' activities.

Perhaps more surprisingly, during unoccupied days when, for security reasons, the schools' windows and doors are expected to be closed, examination of figure 2a shows that the SAMHE 24-hour mean $PM_{2.5}$ concentrations do still reach elevated levels when the AURN 24-hour mean $PM_{2.5}$ concentrations are higher (the timing of these non-schooldays is evident on comparing the days for which data is plotted in figure 2a but no data is plotted in figure 2b). Examining the 'continuous period datasets' which include measurements made on non-schooldays and overnights the correlation between the SAMHE and AURN $PM_{2.5}$ concentration measurements remain strong and is not significantly different from that during the schooldays (the Spearman's rank correlation is approximately 0.83, with a p-value of $p < 2.2 \times 10^{-16}$). This suggests that the building envelopes of the UK's SAMHE schools are still relatively permeable to $PM_{2.5}$ even when windows and ventilation openings might be expected to be closed.

The SAMHE $PM_{2.5}$ concentrations examined, which are each means of the values recorded from within schools widely distributed across the UK (see figure 1), are well correlated with the AURN $PM_{2.5}$ concentrations (which are also each means of the values recorded at AURN sites across the UK, see also figure 1) — the datasets exhibiting such a clear correlation between the indoor school concentrations and the outdoor concentrations is noteworthy because of the scale of the datasets. As such, it is a notable finding that trends in $PM_{2.5}$ concentrations within UK schools are strongly linked to $PM_{2.5}$ concentrations in ambient outdoor air at a national scale.

There is a range of potential sources of particulate matter that can be generated in school classrooms, which include organic sources such as skin flakes and clothes fibres as well as chalk (where still used) and particles generated from building deterioration (Son, 2023; Amato et al., 2014; Becerra et al., 2020). Moreover, the concentration of $PM_{2.5}$ in classrooms has been found to be closely correlated to the activity level of pupils in the classroom, especially as occupant activity plays a key role in the re-suspension of settled particles, (Son, 2023; Becerra et al., 2020). It is desirable to estimate how much of the $PM_{2.5}$ measured in schools might be due to their production therein. To do this, we examine average $PM_{2.5}$ concentrations, within the two relevant periods, over the whole academic year. Taking the continuous period datasets, i.e. based on the 24-hour means and including non-schooldays, the average of the AURN data (measured outdoors) is $3.26\,\mu g/m^3$ higher than that of the SAMHE data, measured in schools. However, when examining the schoolday datasets, i.e. based on the 09:00-16:00 means only on schooldays during which in-school sources are generated and there may also be a higher infiltration from outdoors, this difference falls to $2.14\,\mu g/m^3$. This is a result that would be obtained if, all else remained equal and, during school hours the production of $PM_{2.5}$ indoors was sufficient to increase the $PM_{2.5}$ concentration by, on average, $1.12\,\mu g/m^3$. This is significant finding, given that average of school-year SAMHE dataset over the whole academic year is $4.54\,\mu g/m^3$ and we therefore assert that, a reasonable upper bound for, the fraction of $PM_{2.5}$ measured in schools that is due to sources within the schools, might be approximately 25%.

### *3.2. Examining the data through '$PM_{2.5}$ event' periods, based on outdoor concentrations*

Our results (§3.1) evidence the strong correlation between outdoor and school $PM_{2.5}$ concentrations; consequently, we seek to investigate the impact of periods of high outdoor $PM_{2.5}$ concentrations, herein '$PM_{2.5}$ events', on the concentrations measured in schools. As described (§2.3), $PM_{2.5}$ events are defined as any day, or set of consecutive days, when the AURN 24-hour mean $PM_{2.5}$ concentration exceeds some threshold value, herein we investigate two event types based on two differing threshold values, namely: "WHO $PM_{2.5}$ events" defined based on a threshold value of $15\,\mu g/m^3$ (taking the 24-hour mean health-based limit recommended by the World Health Organisation, WHO), and "Moderate $PM_{2.5}$ events" for which the threshold is set to be the median plus, one standard deviation, of the 'continuous period AURN dataset', this threshold has the value of $9.67\,\mu g/m^3$. The median being selected since it is less affected by outliers than the mean, but we note that threshold is entirely dependent on the measured concentrations, unlike that for WHO $PM_{2.5}$ events. Moreover, any particular threshold could have been chosen, the choice being somewhat arbitrary; however, in choosing a smaller value than the WHO guideline, Moderate $PM_{2.5}$

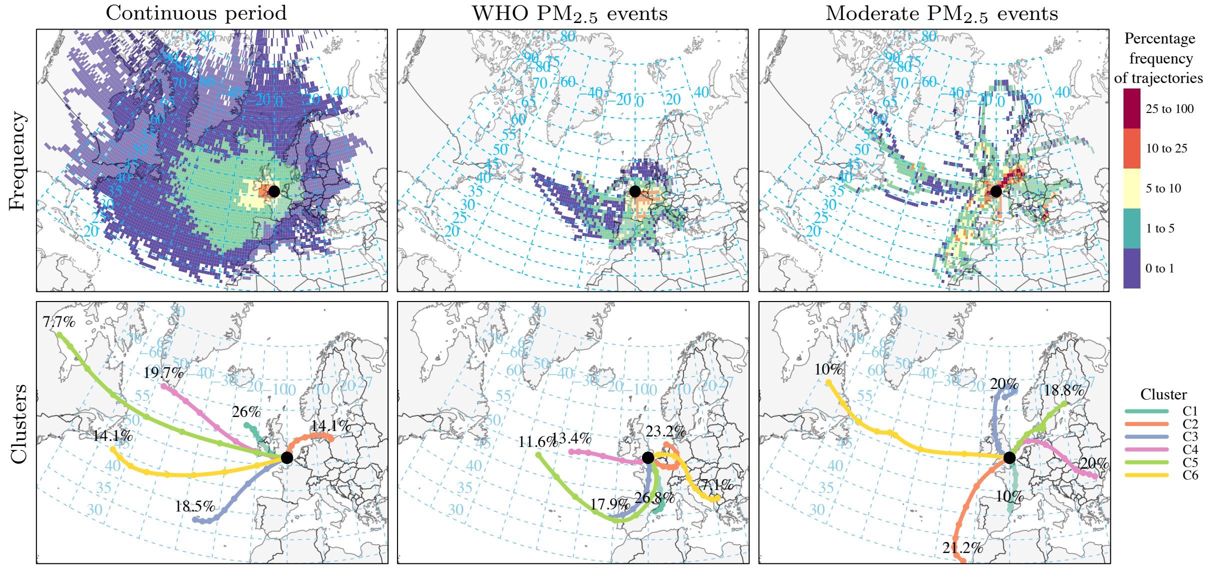



Figure 3: Illustration of the (four-day) air-mass back trajectories arriving at the London Honor Oak Park AURN site (each calculated at three-hour intervals), segregated based on arrival times during: a) the whole duration of the continuous period (first column), b) during WHO $PM_{2.5}$ events (second column), and c) during moderate $PM_{2.5}$ events (third column). The first row indicates, though the colour shading, the frequency with which the trajectories passed through the longitude-latitude grid cells. The second row shows the results of the cluster analysis (see Appendix D for details) for the respective trajectories.

events seek to analyse the impact on school air quality of the more frequent but less extreme outdoor $PM_{2.5}$ events.

Identifying particular $PM_{2.5}$ events enables examination of the climatic conditions associated with their occurrence. Analysis of air-mass back trajectories (see Appendix D for a full description of the method employed) was also carried out to, where possible, infer where sources of $PM_{2.5}$ might have geographically originated from. A ‘trajectory’ is based on simplified weather data and represents the movement of the centroid of a mass of air over a number of days. Back trajectories indicate where air-masses that arrived at a specific location and time, might have originated from (for a comprehensive decription of trajectories and their calculation see Fleming et al., 2012). For our purposes, it was important to determine if the back trajectories of air-masses arriving at a single location in the UK might be broadly representative of those air-masses arriving elsewhere in the UK. As such, we calculated trajectories at a location in the south of the country, at London Honor Oak Park AURN site, and at a location in the north of the country, Auchencorth Moss AURN site, located south of Edinburgh. The analysis of trajectories at these two locations were qualitatively compared and found to reveal similar air-mass trajectories. For convenience of presentation, only the trajectories for the London Honor Oak site are presented herein.

### 3.2.1. *WHO $PM_{2.5}$ events*

During the continuous period (academic year 2023–2024) four WHO $PM_{2.5}$ events occurred. These are highlighted by the vertical light-green panels in figure 2, and the dates are summarised in table E.1. Elevated levels of $PM_{2.5}$ concentration are evident in schools during all of the WHO $PM_{2.5}$ events (e.g. see figures 2a and 2b, with the associated indoor measurement themselves typically exceeding the WHO threshold. The indoor-outdoor ratio during the first WHO $PM_{2.5}$ event, during September, is significantly higher than during the other events. This period of time coincided with the start of the school term for English and Welsh schools, and it is possible that a greater amount of dust, that had settled over the summer holiday, might have been re-suspended by activities on these schooldays — a hypothesis loosely supported by the indoor-outdoor ratio, during this WHO $PM_{2.5}$ event, being greater based on the schoolday means than that of the 24-hour means. On the day following each WHO $PM_{2.5}$ event, the SAMHE schoolday mean $PM_{2.5}$ concentration reduced below the threshold, indicating the residence time of the $PM_{2.5}$ within schools is not longer than a day.

The second column of figure 3 shows that the back trajectories of air-masses arriving in London during the WHO $PM_{2.5}$ events have (over the four days prior to their arrival) predominantly spent time over Europe; mostly over France, Belgium and Germany. By contrast, the first column of figure 3 shows that, averaged over the whole continuous period, the trajectories more frequently arrive from over the Atlantic Ocean and are very different to those determined for WHO $PM_{2.5}$ events. The air-masses that arrived during WHO $PM_{2.5}$ events could have carried sources of $PM_{2.5}$ generated in Northern Europe to the UK, as has been recorded to frequently occur in the past (Harrison et al., 2012; Malley et al., 2016; Graham et al., 2020).

#### *3.2.2. Moderate $PM_{2.5}$ events*

Based on our definition and data, a 'moderate' outdoor $PM_{2.5}$ event occurred when the outdoor 24-hour mean $PM_{2.5}$ concentration exceeded $9.67\,\mu g/m^3$ — the median plus one standard deviation of the continuous period AURN dataset (indicated by the dot-dash lines in figure 2). There were 17 periods when a moderate $PM_{2.5}$event was determined to have occurred, as shown by the dark green panels in figure 2. Note that some of these $PM_{2.5}$ events occur on the days before and after some of the WHO $PM_{2.5}$ events. The dates of the 17 moderate $PM_{2.5}$ events recorded are summarised in table E.2 which also shows that whilst these $PM_{2.5}$ events occurred over 28 days, only ten of these were schooldays. Most of the moderate $PM_{2.5}$ events are of shorter duration relative to the WHO $PM_{2.5}$ events.

Elevated $PM_{2.5}$ concentrations are detected in schools during these moderate $PM_{2.5}$ event. However, only during four moderate $PM_{2.5}$ events (out of 17) did a SAMHE schoolday mean $PM_{2.5}$ concentration exceed the threshold, *cf.* the WHO $PM_{2.5}$ events. Consistent with the WHO $PM_{2.5}$ event data, even if an event raised the $PM_{2.5}$ concentration in schools over a weekend, the effect of the event is typically not evident on the following schoolday.

The clustered back trajectories of air-masses arriving into London during the moderate $PM_{2.5}$ events, as shown in the third column of figure 3, are distinctly different to those during WHO $PM_{2.5}$ events (shown in the second column), indicating that the conditions that cause elevated AURN $PM_{2.5}$ concentrations are not common to both types of events. Air-masses that travel over Europe during moderate $PM_{2.5}$ events are described by 48.8% of the clustered trajectories, as compared with 86.6% of trajectories during WHO $PM_{2.5}$ events. Unlike during WHO $PM_{2.5}$ events, air-masses travel other parts of the UK and more frequently over the Atlantic ocean. Clustered trajectories that travel over the Atlantic, which typically introduce little to no $PM_{2.5}$ to the air-masses, represent 31.2% of trajectories during moderate $PM_{2.5}$ events. The clustered trajectories that travel over the UK during moderate $PM_{2.5}$ events are shorter than other trajectories, showing the air-masses associated with these trajectories were slower moving, which would allow sources to accumulate in the outdoor air of the UK. A higher proportion of trajectories travelling over the Atlantic and slow moving air-masses over the UK would suggest that sources of $PM_{2.5}$ generated within the UK contribute significantly to causing moderate $PM_{2.5}$ events.

### *3.3. Exploring the implication by examining the exposure potential*

School air quality is important because of the potential for relatively long duration exposures to occur there. As such, we calculate estimates of the potential dose of $PM_{2.5}$ that might, on average, be received in a school. For each minute of every schoolday, an average concentration, $C$ ($\mu gm^{-3}$), is calculated from the $PM_{2.5}$ concentrations measured at included schools. From this, an estimate of potential dose ($\mu$g) is calculated on each schoolday by integrating the product of $C$ and an average breathing rate, $Q_b$, over the duration of the school day. For the breathing rate, we take $Q_b = 0.012\,m^3 min^{-1}$, based on the average breathing rate of children with ages in the range [6,16) doing light intensity activity, as recommended for short-term inhalation exposures, see EPA (2011). Herein, SAMHE $PM_{2.5}$ concentrations of minutely frequency are used, Appendix B discusses the consequences of using hourly or daily averaged data.

The total potential dose over the entire school-year was estimated to be $3\,041\,\mu$g. The contribution to the total dose from different concentration ranges, segregated into discrete concentration bins of $1\,\mu g/m^3$ in width, is shown in figure 4a. Two distinct modes exist, below and above 15 $\mu$g/m$^3$ (coincidentally the WHO guideline threshold value), and most of the potential dose over a school-year is due to $PM_{2.5}$ exposures during non-event days, i.e. on days for which the mean of the AURN dataset remained below the threshold of its median plus one standard deviation — these constitute the majority of days.

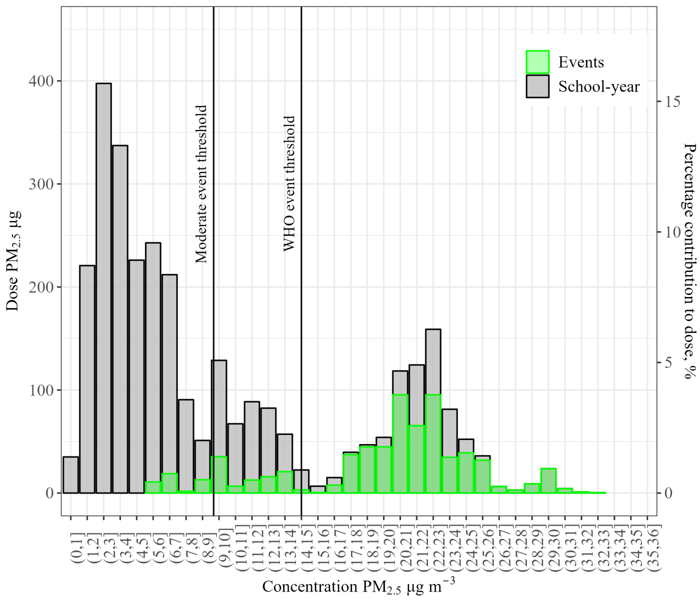
The potential dose during $PM_{2.5}$ events is simply calculated by summing the potential doses associated with each schoolday on which the relevant $PM_{2.5}$ event criteria was satisfied. The contribution of different concentrations to the potential dosage associated with $PM_{2.5}$ events is overlaid in figure 4a as green bars. Since moderate $PM_{2.5}$ events are defined when that day's AURN 24-hour mean $PM_{2.5}$ concentration exceeds 9.67 $\mu$g/m$^3$ and §3.1 evidences strong correlations between concentrations outdoors and those in school, it is not surprising that during events the potential dose is associated elevated with elevated concentrations within the schools, with most of the contribution to dose associated with concentrations greater than 15 $\mu$g/m$^3$. It is also notable from figure 4a that some of the potential dose associated with high concentrations in schools does occur outside of $PM_{2.5}$ events.

Although the majority of the total potential dose over a school-year is estimated outside of $PM_{2.5}$ events, the dose received during $PM_{2.5}$ events is significant — our estimates indicate they contribute 41% of the total potential dose whilst only occurring on 13% of days. The dose received during WHO $PM_{2.5}$ events is more significant still, exacerbated by their relatively long durations. WHO $PM_{2.5}$ events contribute 27% of the total potential dose and account for 6% of the school-year; moderate $PM_{2.5}$ events account for 14% of the total potential and occurred on 7% of the school-year. We note that the potential dose calculations only consider the dose received whilst pupils are at school. This can be a significant proportion of their dose (some estimates suggest that 30%–40% of a yearly-averaged child's daily (24-hour period) dose is recieved in the classroom Rivas et al., 2016; Faria et al., 2020); however, children are exposed to $PM_{2.5}$ in other indoor environments as well as outdoors, most notably whilst commuting to and from school (Correia et al., 2020; Varaden et al., 2019; Nieuwenhuijsen et al., 2015). Additionally, outdoor $PM_{2.5}$ events more frequently occur during the school-year than during the summer holidays (Kelly et al., 2023; Abdalmogith and Harrison, 2005), the longest period for which pupils are not in school. As such, the contribution of outdoor $PM_{2.5}$ events to a child's total potential dose over the entire calendar year (September 2023 to August 2024) would be considerably lower.

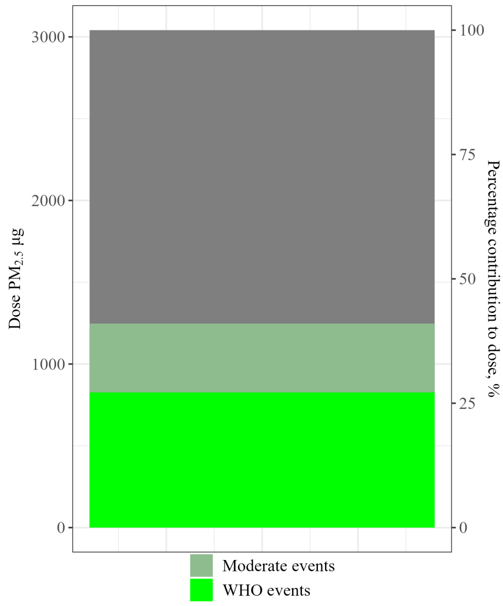
## 4. Conclusions

Analysis of the concentrations of $PM_{2.5}$ recorded by 490 SAMHE monitors in schools, across the UK, during the academic year 2023–2024 were reported. Local and regional variations in ambient outdoor $PM_{2.5}$ concentrations are well documented (Harrison et al., 2012), despite these, and the likely variation in activities and air quality between classrooms (Burridge et al., 2023), significant correlations in classroom $PM_{2.5}$ were evident on a national scale— indicating that large-scale pollution events across the nation have a significant impact on classroom air quality. During periods of elevated ambient outdoor $PM_{2.5}$ concentrations — outdoor $PM_{2.5}$ events — the concentration in schools was also found to be significantly elevated. The data showed that these included events where the 24-hour mean health-based limit (15 $\mu$g/m$^3$) recommended by the World Health Organisation was exceeded within schools. These WHO $PM_{2.5}$ events have a significant impact on the long-term dose over a school-year, contributing to 27% of the total potential dose whilst only occurring on 6% of the schooldays over the year. Back trajectory analysis reveals that WHO $PM_{2.5}$ events are caused by sources which have specific geographical locations. In mitigating children's exposure to $PM_{2.5}$, some consideration could be devoted to periods of elevated outdoor $PM_{2.5}$ concentrations; for example, when $PM_{2.5}$ pollution forecasts are high, changes in the operation of school ventilation or air cleaners/filters (noting that any reduction in ventilation risk increasing pollution from indoor sources, including respiratory aerosols) could be considered as a response. However, we note that any suggestion of a response to such periods involving a reduction in attendance at schools, risks increasing children's exposures elsewhere (e.g. in homes where cooking and sources of combustion are more prevalent) and would negatively impacts on their education and socialisation.

We conclude that, whilst there are significant indoor sources of $PM_{2.5}$ in schools, $PM_{2.5}$ incoming as outdoor air ventilates schools and classrooms appears to be the major source. School buildings in the UK




(a)




(b)

Figure 4: (a) Grey bars indicate the contribution to the total potential dose during the school-year apportioned, into 1 $\mu$g/m$^3$ wide bins, by the minutely SAMHE $PM_{2.5}$ concentrations, overlaid in green are those associated with $PM_{2.5}$ event periods. Vertical black lines mark the values of the $PM_{2.5}$ events thresholds. (b) Bar chart showing the total potential dosage over the school-year: the bright-green region indicates the potential dosage associated with WHO $PM_{2.5}$ events, the dark-green region that associated with moderate events, and the grey region indicates potential dosage associated with day outside of $PM_{2.5}$ events.

are permeable to $PM_{2.5}$, even when unoccupied and ventilation openings are expected closed, and this has serious implications for schools' heating costs in the context of the UK government's Net Zero Strategy. This study further highlights the need for continued longitudinal measurements of air quality in schools, and other indoor spaces, which may provide insights into the impact of seasonal pollution patterns on air quality indoors, with potential to evidence the need, and identify efficient routes, to mitigate.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### Data Statement

The authors do not have permission to share data.

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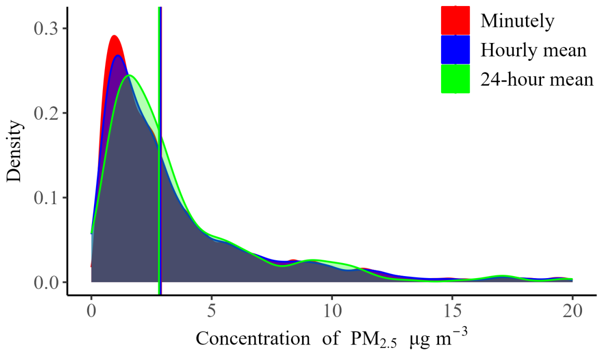
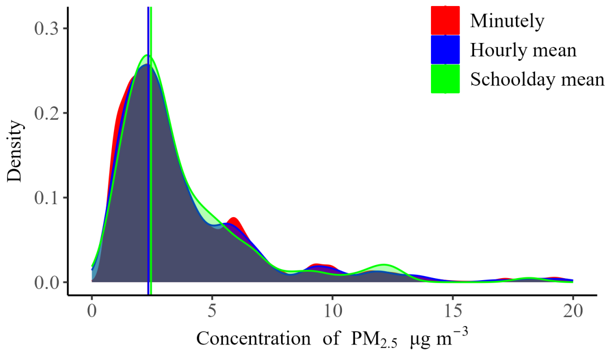
| | First day of term | Last day of term | No of days | No of schooldays |
|---|---|---|---|---|
| Autumn term before half-term | 5th September | 13th October | 39 | 29 |
| Autumn term after half-term | 6th November | 15th December | 40 | 30 |
| Spring term before half-term | 9th January | 9th February | 32 | 24 |
| Spring term after half-term | 26th February | 22nd March | 26 | 20 |
| Summer term before half-term | 16th April | 3rd May | 18 | 14 |
| Summer term after half-term | 3rd June | 25th June | 23 | 17 |

Table A.1: School terms that make up what is considered the school-year within this study.




(a)




(b)

Figure B.1: (a) The probability density functions for the continuous period SAMHE dataset with differing averaging periods: minutely (red), hourly (blue), and 24-hour mean (green); (b) the equivalent for the SAMHE schoolday data. In each, vertical lines mark the median values of each distribution, which are effectively coincident for the minutely, and hourly-averaged, data.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## Appendix A. School term dates

The dates of school terms and holidays differ between Scotland, Northern Ireland, and England and Wales. A set of dates was chosen to define the schoolday datasets by first defining ‘schools terms’ within which schools in all four nations might be active, with pupils in attendance, during the school week (Monday to Friday). The dates used to define these ‘terms’ are summarised in table A.1. Thereafter, any public holiday, within any of the four nations, falling within there ‘terms’ was further excluded from the schoolday datasets.

## Appendix B. Evaluation of the impact of varied time resolution

With access to minutely $PM_{2.5}$ concentration measurements on which to construct the SAMHE datasets, we explore the impact of time averaging the data over differing periods. For example, herein the primary datasets were constructed by taking the data from each included SAMHE monitor and averaging over a 24-hour period in the case of the continuous dataset, and the school day (09:00-16:00) in the case of the schoolday dataset — and then, in both cases, averaging across the included SAMHE schools. However, one could equally construct datasets by taking the data from each included SAMHE monitor (that satisfy the

| | Continuous period data | | | School-year data | | |
|---|---|---|---|---|---|---|
| | mean | standard deviation | median | mean | standard deviation | median |
| **Primary SAMHE datasets** | **3.71** | **3.68** | **2.46** | **4.54** | **4.80** | **2.81** |
| SAMHE datasets with hourly averaging | 3.71 | 3.92 | 2.35 | 4.54 | 4.85 | 2.88 |
| SAMHE datasets with minutely data | 3.71 | 3.93 | 2.34 | 4.54 | 4.85 | 2.89 |
| Alternate SAMHE datasets | 3.62 | 3.64 | 2.41 | 4.39 | 4.68 | 2.71 |

Table B.1: Table comparing summary statistics of differing datasets; the mean, standard deviation and median are presented for the continuous period datasets, and for the SAMHE schoolday datasets, in each case. The first row shows statistics for the primary datasets reported herein, the second row statistics from datasets constructed with hourly-averaged datasets, the third row shows statistics from datasets constructed with minutely data, and the bottom row shows statistics from the datasets constructed using the alternate data completeness criterion.

primary data completeness criteria) and averaging over a period of one-hour, or take the minutely data, and, again, in all cases then average over the SAMHE included schools — the latter creating datasets of "SAMHE minutely $PM_{2.5}$ concentration" (which prove of value when assessing the potential dose, see below). Figure B.1 shows probability density functions associated with three different averaging periods (the primary data in green, hourly minutely in blue, and minutely in red) for: (a) the continuous period data, and (b) the schoolday data. Whilst figure B.1a does indicate some differences, e.g. the peak (modal) values of the SAMHE 24-hour mean $PM_{2.5}$ concentration distributions, table B.1 shows the key metrics of the distributions differ insignificantly in all cases. We therefore conclude that analysis of SAMHE 24-hour mean $PM_{2.5}$ concentrations (i.e. the SAMHE continuous datasets) and SAMHE schoolday mean $PM_{2.5}$ concentrations (i.e. the SAMHE schoolday datasets) is appropriate and is presented herein.

The potential dose that pupils might receive was estimated using SAMHE minutely $PM_{2.5}$ concentrations, rather than SAMHE $PM_{2.5}$ concentrations over some longer period. To investigate the sensitivity of the finding to that choice, we compare the probability density of potential dose as a function of concentration. Figure B.2 shows the contribution to the total potential dose from different concentrations, segregated into discrete concentration bins of $1\,\mu g/m^3$ width. The distribution of potential dose is shown for the primary (minutely) SAMHE data (red), with the distributions overlain for the results based on hourly averaging (blue), and averaging over the schoolday (green) of $PM_{2.5}$ concentration data. The potential dose calculated using the primary SAMHE minutely $PM_{2.5}$ concentrations has contributions from every concentration bin up to and including $33\,\mu g/m^3$. The potential dose calculated using SAMHE hourly $PM_{2.5}$ concentrations leads to a similar distribution at concentration ranges below $15\,\mu g/m^3$; however, for higher concentration ranges, the dose calculated using SAMHE minutely $PM_{2.5}$ concentrations is not well represented by the dose calculated using SAMHE hourly $PM_{2.5}$ concentrations. The potential dose calculated using SAMHE schoolday mean $PM_{2.5}$ concentrations shows that the distribution is less well represented still. As such, we regard it as necessary to use high resolution $PM_{2.5}$ concentration data, ideally minutely, when making calculations to estimate the potential dose.

## Appendix C. Evaluation of data completeness criteria for selection of $PM_{2.5}$ concentration data

The results in §3 report trends of the primary datasets; namely, the continuous datasets and the schoolday datasets. The data completeness criteria, as detailed in §2.2, specified that on each day, data would be selected from only schools that reported data for over 75% of: the 24-hour period, in the case of the continuous datasets, or the school day (09:00—16:00) for the schoolday dataset. To test the sensitivity of the results to the choice this criteria, alternate datasets were created using alternate data completeness

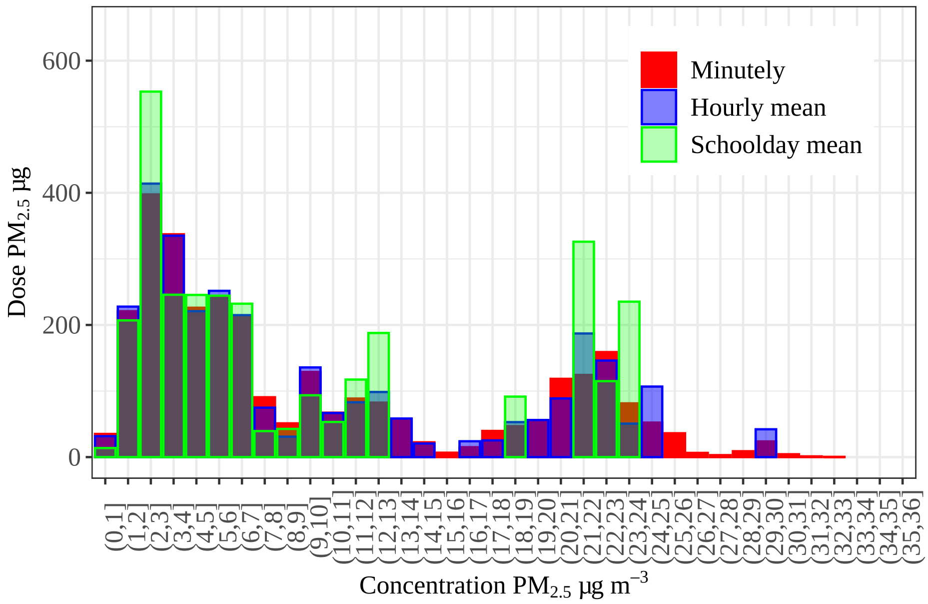


Figure B.2: The contribution to the total dose during the school-year due to $PM_{2.5}$ concentrations apportioned in to $1\,\mu g/m^3$ bins. The dose calculated from SAMHE minutely $PM_{2.5}$ concentrations, as presented in §3.3 is shown in red, and in blue and green are the doses calculated using the SAMHE hourly mean and SAMHE schoolday mean $PM_{2.5}$ concentrations, respectively.

criteria. The alternate data completeness criteria specified that, in addition to the criteria of the primary datasets, data is only selected from schools that report adequate data on more than 75% of days within the entire school-year. Table B.1 shows the mean, standard deviation and median calculated across all 295 values of the SAMHE 24-hour mean $PM_{2.5}$ concentrations in the continuous period datasets, and all 133 values of SAMHE schoolday mean $PM_{2.5}$ concentrations in the schoolday datasets, formed by both the primary and alternate data completeness criterion. Over the entire continuous period, should the alternate criteria have been selected, the mean would have been $0.09\,\mu g/m^3$ (or 2.43%) lower than the primary dataset, the median would have been $0.05\,\mu g/m^3$ (2.03%) lower, and the standard deviation $0.04\,\mu g/m^3$ (or 1.09%) lower, than for the primary dataset. Likewise, for the SAMHE schoolday data the mean would have been $0.19\,\mu g/m^3$ (or 4.1%) lower, and would the median and the standard deviation, by $0.07\,\mu g/m^3$ (2.52%) and $0.13\,\mu g/m^3$ (2.7%), respectively. To summarise, the choice of dataset construction between the primary datasets (in which included schools evolve throughout the year) and the alternate datasets (in which the population of included schools remains fixed throughout the year) does not result in significant differences in the reported results and does not affect any of the conclusions drawn.

## Appendix D. Air-mass back trajectory analysis

Back trajectories were calculated using HYSPLIT (Hybrid Single Particle Lagrangian Integrated Trajectory) model, an atmospheric transport and dispersion model (see Stein et al., 2015, for full details). Gridded meteorological data (e.g. wind speed and direction, temperature, humidity, and precipitation) from the NCEP-NCAR Reanalysis meteorological model (Kistler et al., 2001) constitute inputs of the HYSPLIT model, which is run using the Openair R statistical software package (Carslaw and Ropkins, 2012). For an initial start location (longitude, latitude, and altitude) and time (the time that the air-mass arrives to the chosen location — herein London Honor Oak Park AURN site, see §3.2 for a discussion), the HYSPLIT model calculates the movement of a parcel of air due to the mean advection by wind using a Lagrangian method, iterating backwards in time at intervals of one hour for a duration of 96 hours (4 days) to calculate a given back trajectory. Back trajectories are presented based on air-masses arrival times, at the chosen

| Event | Start date | End date | Number of days | Number of schooldays |
|---|---|---|---|---|
| 1 | 06/09/2023 | 10/09/2023 | 5 | 3 |
| 2 | 06/03/2024 | 11/03/2023 | 6 | 4 |
| 3 | 02/05/2024 | 02/05/2024 | 1 | 1 |
| 4 | 11/05/2024 | 12/05/2024 | 2 | 0 |

Table E.1: A complete list of the dates, and their durations in terms of days and schooldays, for the 'WHO $PM_{2.5}$ events' analysed.

| Event | Start date | End date | Numer of days | Number of schooldays |
|---|---|---|---|---|
| 1 | 05/09/2023 | 05/09/2023 | 1 | 1 |
| 2 | 16/09/2023 | 17/09/2023 | 2 | 0 |
| 3 | 09/10/2023 | 10/10/2023 | 2 | 2 |
| 4 | 12/11/2023 | 12/11/2023 | 1 | 0 |
| 5 | 16/11/2023 | 16/11/2023 | 1 | 1 |
| 6 | 25/11/2023 | 26/11/2023 | 2 | 0 |
| 7 | 29/11/2023 | 29/11/2023 | 1 | 1 |
| 8 | 01/12/2024 | 03/12/2024 | 3 | 1 |
| 9 | 06/12/2024 | 06/12/2024 | 1 | 1 |
| 10 | 13/01/2024 | 13/01/2024 | 1 | 0 |
| 11 | 24/01/2024 | 24/01/2024 | 1 | 1 |
| 12 | 29/01/2024 | 29/01/2024 | 1 | 1 |
| 13 | 31/03/2024 | 31/03/2024 | 1 | 0 |
| 14 | 01/05/2024 | 01/05/2024 | 1 | 1 |
| 15 | 06/01/2024 | 10/01/2024 | 5 | 0 |
| 16 | 13/05/2024 | 13/05/2024 | 1 | 0 |
| 17 | 18/05/2024 | 20/05/2024 | 3 | 0 |

Table E.2: A complete list of the dates, and their durations in terms of days and schooldays, for the 'moderate outdoor $PM_{2.5}$ events' analysed.

location, every three-hours over the academic year. The trajectories of air-masses that arrive at the chosen location during $PM_{2.5}$ events are compared to those that arrive at the chosen location at other times of the academic year, to determine if there are air-mass trajectories are qualitatively different during $PM_{2.5}$ events. Cluster analysis of trajectories was also conducted to objectively group trajectories based upon similarities in the paths they take. This analysis was conducted using the 'trajCluster' package within Openair, (Carslaw and Ropkins, 2012) which determines how similar two trajectories are by calculating the Euclidean distance between the 96 longitude and latitude coordinates along each trajectory (96 points for each 96 time iterations) using a Haversine formula.

## Appendix E. Dates of outdoor $PM_{2.5}$ events

In §3.2 the impact of periods of elevated AURN $PM_{2.5}$ concentrations, or '$PM_{2.5}$ events', on the SAMHE $PM_{2.5}$ concentration was investigated. Two definitions of $PM_{2.5}$ events were evaluated. Namely, 'WHO $PM_{2.5}$ events', which is any day, or consecutive days, for which the AURN 24-hour mean $PM_{2.5}$ concentration exceeds 15 $\mu$g/m$^3$, and 'Moderate $PM_{2.5}$ events' are defined as when the AURN 24-hour mean $PM_{2.5}$ concentration exceeds 9.67 $\mu$g/m$^3$. The dates on which these events occurred, and their durations in days and schooldays, are summarised in tables E.1 and E.2, respectively.