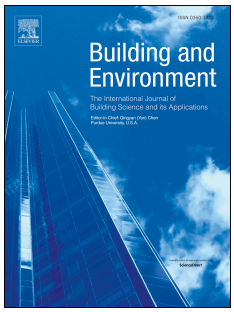
Journal Pre-proof



Long-term, continuous air quality monitoring in a cross-sectional study of three UK non-domestic buildings

Samuel Stamp, Esfand Burman, Clive Shrubsole, Lia Chatzidiakou, Dejan Mumovic, Mike Davies

PII: S0360-1323(20)30451-0

DOI: https://doi.org/10.1016/j.buildenv.2020.107071

Reference: BAE 107071

To appear in: *Building and Environment*

Received Date: 4 May 2020

Revised Date: 12 June 2020

Accepted Date: 13 June 2020

Please cite this article as: Stamp S, Burman E, Shrubsole C, Chatzidiakou L, Mumovic D, Davies M, Long-term, continuous air quality monitoring in a cross-sectional study of three UK non-domestic buildings, *Building and Environment* (2020), doi: https://doi.org/10.1016/j.buildenv.2020.107071.

Long-term, continuous air quality monitoring in a cross-sectional study of three UK non-domestic buildings

Samuel Stamp[a], Esfand Burman[a], Clive Shrubsole[b], Lia Chatzidiakou[c], Dejan Mumovic[a], Mike Davies[a]

[a] Institute for Environmental Design and Engineering, University College London (UCL), Central House, 14 Upper Woburn Place, London, WC1H 0NN, UK

[b] Air Quality & Public Health Group, Environmental Hazards and Emergencies Department, Centre for Radiation, Chemical and Environmental Hazards, Public Health England, Harwell Science and Innovation Campus, Chilton, Oxon, OX11 0RQ, UK

[c] Department of Chemistry, University of Cambridge, Cambridge, CB2 1EW, UK

Corresponding author: samuel.stamp@ucl.ac.uk

Abstract

Long-term, continuous air quality monitoring has been carried out alongside seasonal passive sampling within a case study a hospital, school and office building, representing a cross-section of the UK non-domestic sector. This approach aimed at adopting state of the art sensor technology to provide a greater understanding of the variations in indoor air quality over time and how these variations relate to both building operation and occupant behavior. The results highlight how the relationship between indoor and outdoor air evolves considerably on both short and long-term basis, with varying behaviors then seen across different sources of pollutants. The mechanically ventilated hospital and school buildings demonstrate the effectiveness of particulate filters, with very low internal concentrations of $PM_{2.5}$. However, high ventilation rates, combined with the absence of any filtration of NO_2, resulted in the hospital having the highest indoor concentrations of NO_2 and the highest associated indoor-outdoor ratio. Morning and evening traffic related peaks in NO_2 can be observed indoors, with their penetration dependent upon the delivered ventilation rates. This demonstrates the impact of adopting high ventilation rates during peak traffic, and the consequences of CO_2 based demand-controlled ventilation systems in polluted urban areas without full filtration. The naturally ventilated office then demonstrates significant seasonal variations, with increased ventilation openings resulting in indoor NO_2 concentrations in the summer exceeding

those in the winter, despite significant reductions in ambient levels. Conversely, concentrations of indoor pollutants are seen to reduce with increasing ventilation rates, demonstrating the complex balance between the dilution of indoor pollutants and penetration of outdoor sources. Despite significant reductions from the winter to the summer (21.6 – 11.2 μg/m^3), all formaldehyde measurements in the naturally ventilated office exceeded guideline values, indicating improved guidance and product labelling schemes may be required to achieve these guideline concentrations and reduce associated health risks.

1. Introduction

Links between air quality and health have long been established, with evidence from large, multi-year epidemiological studies dating back several decades (1,2). Premature deaths from poor air quality have been primarily linked to cardiovascular and pulmonary diseases (3). More recent studies have provided suggestive evidence of links to an increasingly wide range of damaging health outcomes including dementia (4), miscarriage (5) and mental health problems (6), with a recent global review indicated that almost every cell in the human body may be affected by exposure to air pollution (7). At the same time, studies have indicated such health risks may be associated with lower concentrations of pollutants and that even the 10% of the global population currently living under WHO limits (8) may still be substantially affected by air pollution (9). Equally, studies have indicated that improvements in air quality lead to improved health outcomes demonstrating the benefit of actions to reduce the presence of pollutants (10).

These results stress the importance of reducing exposure, including within indoor environments where people are estimated to spend 80-90% of their time (11). In principle, buildings may act to protect their occupants from outdoor pollution, limiting exposure levels. However, this role is complicated by the presence of indoor sources of air pollution from buildings materials, furnishings and indoor activities (12). Balancing the removal of indoor pollutants with a reduction in the ingress of outdoor sources remains a significant challenge, particularly as buildings must also be designed

and operated to deliver other forms of comfort (e.g. thermal, acoustic) and meet sets of broader goals (e.g. financial, energy targets). If exposure within indoor environments is going to be effectively reduced, there remains a need to fully understand effective design and operation strategies, particularly in the context of delivering, sustainable, low-energy buildings

Over the last three decades, a wide range of studies have looked to build up a picture of indoor air quality (IAQ) and have begun to identify key drivers affecting indoor air quality. Results have indicated the influence of building materials (13–15), finishes (e.g. carpets (16)), occupancy and activity (17–21), including window opening (22,23). Pollutants present in outdoor air, along with proximity to roads, has then been shown to correlate strongly with indoor concentrations of particulates and nitrogen dioxides (NO_2) (14,24,25), with seasonal variations in outdoor pollutants mirrored in indoor concentrations (18,26). Seasonal trends have then also been observed in indoor concentrations of VOCs (26,27)

The impact of delivering low-energy buildings upon IAQ has also been examined. Trends for improved airtightness seem to have a negligible impact on the ingress of pollutants form outdoors (17,28,29) and rather may increase the risk of the build-up of internal pollutants (30,31). Ventilation rates and systems have generally been found to be more influential, with increased ventilation provision decreasing indoor contaminates or vice versa (29,31–33) and mechanical filtration reducing the penetration of particulates in school (29) and hospitals settings (34). However, the role of ventilation provision is not straightforward. Stabile et al., (2017) found longer periods of window opening lead to reductions in indoor VOCs but increased ingress of fine particulate matter, whilst Langer et al., (36) found increased ventilation rates reduced formaldehyde and $PM_{2.5}$ concentrations but increased the ingress of toluene. Further, Bozkurt et al., (37) found under ventilated classrooms had a lower penetration of NO_2 from outdoors, whilst Zhang et al. (38) reported window opening in Chinese classrooms reduced CO_2 but increased both NO_2 and SO_2 from outdoors.

Many of these studies have used diffusive sampling tubes, measuring average concentrations over periods of several days to weeks. They therefore may lack dynamic information which may relate to daily building operations or short-term behaviours and activities. Continuous, time-based measurements (e.g. logging every 5mins) have traditionally been more expensive, labour intensive and intrusive, limiting both the range and length of studies, typically between a few days or single week (e.g. 13,16,21,34,35), with only more recent studies extending monitoring for several months (e.g. 36,37)

However, the development of lower cost air quality sensors has already provided higher spatial resolution within urban environments, improving understanding of outdoor pollution distribution, sources and personal exposure. Previous studies (43,44) have indicated that after appropriate calibration, the performance of novel technologies is comparable to that of certified instrumentation at levels commonly encountered in indoor microenvironments. In the context of the indoor built environment, such sensor technologies can provide dynamic information, both of short-term building operation and longer-term seasonal trends with long term deployments. It is therefore thought that these continuous time-based measurements can then provide further insights into the relationship IAQ has with building operation, ventilation strategies, occupant behaviour and the influence of the external environment.

This paper therefore aims to explore these relationships and dynamics through the use of both long-term continuous measurements and seasonal passive sampling. Selected pollutants have therefore been monitored during heating and non-heating seasons, within three recently constructed case study buildings; a hospital, school and office, with total monitoring periods of between 6-10months in each building. Whilst together, offices, educational buildings and hospitals account for around 65% of the UK non-domestic building stock (45), these cross-sectorial case study buildings act to highlight differences in building use, operation, design and ventilation strategies within modern, low-energy buildings.

2. Method & Materials

To address this aim, two complementary approaches have been taken. Firstly, continuous indoor and outdoor air quality measurements have been made in each case study building for periods of 6-10 months. Details of continuous measurements are described in Section 2.2 and Appendix A. Secondly, additional pollutants, including key VOCs, have been measured via passive sampling techniques across periods of 5-14 days in both the heating and non-heating seasons. This method and the selection of these pollutants are discussed in section 2.3. Finally, a brief description of the three cases study buildings is given in the following section.

2.1 Case study buildings

The three case study buildings all represent modern buildings designed to comply with the energy efficiency requirements prevalent at the time of construction. Each had been occupied for at least 3 years at the start of this study, avoiding issues related to initial commissioning and occupants settling in and aiming to ensure the buildings are being occupied and run under typical operating conditions. Summary details of each case study building can be found in Table 1, whilst each case study is then described in turn.

Table 1: Summary details of three case study buildings.

Building Type	**Hospital**	**School (Secondary)**	**Office (public sector)**
Location	Bristol	South London	Keynsham
Gross Floor Area	15,700 m^2	21,400 m^2	6,400 m^2
Completion	2015	2014	2014
Occupants	150 Staff, 160 Beds	2,000 pupils, 200 staff (nominal)	455 (nominal)
Ventilation Strategy	Mechanical Ventilation (sealed envelope)	Mechanical Ventilation (manually openable windows)	Natural Ventilation (manually openable windows & motorised louvers)
BREEAM rating	Very Good	Very good	Not opted for
EPC (Asset) Rating	B/31 (including CHP)	B/35 (new buildings)	A/5
DEC (Operational) Rating	D/81 (2017)	F/150 (2018)	B/36 (2016)

2.1.1 School case study

The school, constructed from precast concrete façade panels, includes a total six new buildings in a central London site. Built to modern U-value and airtightness standards (< 5m³/hr/m²) in accordance with the 2010 edition of the Building Regulations in England, this secondary school (ages 11-18) has a core timetable running 08:35-15:50 Monday-Friday with additional out of hours and weekend use. Mechanical ventilation with heat recovery is provided by centralised roof mounted air handling units (AHU). Wall mounted diffusers/grills are used to distribute the supply air whilst small openable windows provide additional natural ventilation. Mechanical ventilation provision is then controlled via a Building Management System (BMS) based on installed carbon dioxide sensors in each room. Whilst there are large areas of exposed concrete throughout, other furnishings remain typical of UK schools and have not been specified in relation to their potential off gassing of VOCs. A typical classroom, lab-based classroom and library space across three different blocks have been monitored for this study.

The school sits approximately 8 km from the centre of London, within a residential location, albeit with a busy minor road directly along its north façade. The school has open playing fields to the east and west. The nearest urban background monitoring stations (1.6 km) recorded mean annual concentrations below WHO annual limits for both NO_2 (30 µg/m^3) and PM_{10} (18 µg/m^3) in 2017, the year of the study (46).

2.1.2 Office case study

The office case study building, made up of three interconnecting blocks, is naturally ventilated using cross and stack ventilation facilitated by voids introduced between the floors. There is no mechanical cooling in open plan office spaces and exposed thermal mass is combined with natural ventilation to help regulate internal temperatures in summer. Natural ventilation is provided by both occupant openable window louvers and higher level BMS controlled louvers, themselves operated

based upon indoor CO_2 concentration and external temperatures. Three open plan offices have been monitored continuously for this study, across each of the three blocks at different floor heights.

The building sits at the end of a busy high-street and a short distance from a major bypass. The nearest automatic air quality measurement stations are in the nearby cities of Bristol and Bath.

2.1.3 Hospital case study

The hospital building is located in a city centre with a ventilation strategy based upon mechanical ventilation with high air exchange rates in most spaces (10-12 h^{-1}) with a CO_2 based demand control system. The building has a fully sealed envelope, with no openable windows, an approach aimed at protecting patients and hospital staff against external noise and outdoor sources of pollution. Three wards have been monitored, all similar in use with 4-6 beds and a nurse's station within each. Mechanical ventilation inlets are based next to AHUs on the 7th floor, facing the relatively quieter north façade. To control the risk of infection, wards are cleaned intensively and frequently, creating challenges regarding internal air quality.

The nearest urban background air quality station (< 1 mile) recorded annual mean NO_2 concentrations of 24 µg/m^3, PM_{10} concentrations of 15 µg/m^3 and annual mean concentrations of $PM_{2.5}$ at 11 µg/m^3. Annual $PM_{2.5}$ concentrations are therefore above WHO limits, with 24-hour limits for $PM_{2.5}$ (25 µg/m^3) then breached on 39 days in 2017 (47).

2.2 Long-term continuous air quality monitoring

Continuous air quality sensors measuring particulates (PM_1, $PM_{2.5}$, PM_{10}), nitrogen dioxide (NO_2) and total volatile organic compounds (TVOCs) were installed in 3 different internal zones, covering at least of 5% of the buildings total floor area (BS EN 15251:2007). Environmental measurements including temperature, relative humidity and carbon dioxide (CO_2) were also collected. Data was recorded at 5-minute logging interval in each location and uploaded directly to a secure server via GPRS. Equivalent external air quality measurements were taken on-site, whilst a weather station

measuring local wind speed, direction and global horizontal solar radiation was located on the roof of each case study building.

A sample (n = 4) of integrated sensor units (49) have been co-located with reference instruments obtaining linear correction factors for sensor offsets and sensitivities, following the approach taken by Chatzidiakou et al. (2019). All sensors (n = 15) used in this study have then been run alongside each other in both indoor and outdoor conditions, to extrapolate these correction factors to all sensors and helping to reduce the variation between sensors and overall bias. Further details of this process, co-locations results, data processing and sensor limitations can be found in Appendix A.

Indoor air quality measurements were taken at fixed locations within representative zones within the buildings. Given higher potential spatial variation that may exist around a building, locating external measurement stations is more complex and subject to uncertainty (50). In the case of the mechanically ventilated buildings, external air quality measurements were conducted next to the air intakes, on the roof or top floor of the school and hospital respectively. With multiple supply openings, locating external measurements for the naturally ventilated office case study is less straightforward. External air quality measurements for the naturally ventilated office were therefore taken on the 2nd floor of the 4-storey building. Importantly, this placement of both indoor and outdoor sensors is associated with significant definitional uncertainty - uncertainty resulting from the finite detail within the definition of the measured parameter (51). For example, an indoor-outdoor ratio (I-O) based on an external measurement at location A, will vary to an unknown extent from an I-O based upon an external measurement at point B. The definition of the I-O itself then becomes a significant source of measurement uncertainty and results need careful interpretation.

2.3 Short-term passive sampling

During both the heating and non-heating seasons, additional pollutants have been measured through the use of diffusive sampling techniques. Measurements were carried in the same internal and outdoor locations as the continuous monitoring, for between 5 and 14 days, see Table 2. This list of targeted pollutants reflects both the relative health impact of each pollutant and their prevalence at high levels in other non-residential IAQ studies, along with WHO or Public Health England Guidelines (Table 2). As it is possible to detect more than 250 VOCs in an indoor environment, this list of targeted pollutants is not exhaustive. Previous studies have further indicated xylenes (16,26,29,31), further aldehydes, including acetaldehyde (26,29,31,52–54), elemental compositions of particulate matter (16), polycyclic aromatic hydrocarbons (PAHs), radon (12) and combinations of mould, funghi and bacteria (14,26,34). Results are compared to guideline values for each pollutant from the World Health Organization (12), Public Health England (54) as well as those set as best practice in the context of residential dwellings in IEA-ECB Annex 68 (52). These guideline values can be found in Table 3 alongside measured results

Table 2: Selected pollutants, measurement methods and cited indices studies. Measurement uncertainties are listed under method for diffusive sampling techniques. Continuous measurements included root mean square error (in comparison to reference instruments) and coefficient of variation (CV) comparing variation between sensors. See Appendix A for further details.

Pollutants	**Method**	**Measurement period**	**Studies**
Long-term continuous monitoring			
Nitrogen Dioxide (NO_2)	Electrochemical sensor RMSE = 3.5 ppb CV = 7%	6-10 months	(12,14,17,25,26,31,40,52,53)
Particulates (PM_1, $PM_{2.5}$, PM_{10})	Optical Particle Counter RMSE = 2.1 – 12.6 µg/m^3 CV = 8-14%	6-10 months	(12–14,16,17,25–27,29,40,52,53)
Total Volatile Organic Compounds (TVOCs)	Photoionization detector (PID – Isobutylene) CV = 24%	6-10 months	(13,27,29,31,34,39,52)
Carbon Dioxide	Non-Dispersive	6-10 months	(13,14,27,29,31,34,39,5

(CO_2)	Infra-Red (NDIR) ± (50 ppm) or 3% of measured value		2)
Short-term passive sampling			
Formaldehyde	Passive sampling. BS ISO 16000-4: 2011 High pressure liquid chromatography Measurement Uncertainty ± 14.2%	5 days (heating and non-heating season)	(12–14,16,26,29,31,39,52–55)
Ozone (O_3)	Sampling: n tube) – BS EN 13528 Parts 1-3: 2002/3 Ion Chromatography Measurement Uncertainty ± 10.2%	14 days (heating and non-heating season)	(13,14,16,17,26,34)
Nitrogen Dioxide (NO_2)	Palmes diffusion tube – BS EN 13528 Parts 1-3: 2002/3, Analysis: U.V Spectrophotometry Measurement Uncertainty ± 7.8%	14 days (heating and non-heating season)	(12,14,17,25,26,31,40,52,53)
VOCs (n=8)	Passive (Tenax) – ISO16017-2. Measurement Uncertainty:	5 – 7 days (heating and non-heating season)	
Benzene, toluene, naphthalene, trichloroethylene (T3CE), tetrachloroethylene (T4CE), styrene, d-limonene, α-Pinene	± 17.5% ± 17.5% ± 16.7% ± 12.0% ± 13.6% ± 20.0% ± 10.7% ± 20.8%		(12,14,26,29,52–54) (26,29,31,52–54) (52,53) (12,26,29,52–54) (12,14,26,29,52–54) (26,29,52,53) (14,26,29,52–54) (14,26,29,52–54)

3. Results & Discussion

3.1 Summary of continuous air quality monitoring

The results of continuous IAQ measurements across the three case study buildings are shown in Figure 1-Figure 4. Indoor CO_2 levels (Figure 1) remained <1,000 ppm in almost all zones of the mechanically ventilated buildings. The exception to this, is one school classroom, where higher CO_2 levels are known to be the result of a faulty room-based CO_2 sensor, resulting in lower delivered ventilation rates. The naturally ventilated office experiences higher internal CO_2 concentrations, with mean working hour concentrations just below 1,000 ppm. Again, a faulty CO_2 sensor restricted the activation of automated louvers on the third floor, resulting in higher CO_2 levels within this zone. Discussions with building managers also revealed two further issues. Firstly, many actuators for automated louvers across the building had been installed the wrong way around, severely limiting their ability to open and provide ventilation. Secondly, the use of automated louvers was restricted during the heating season in order to meet operational energy targets – a direct example of balancing IAQ and energy use. These issues highlight and provide further evidence of the influence all stages of design and construction may have upon achieved performance (56), with commissioning, installation and operational strategies having significant impacts here.

Equivalent TVOC measurements (Figure 2) offer both some corresponding and contrasting perspectives to the measured CO_2 levels. Both zones with faulty CO_2 sensors record significantly higher TVOC levels than other zones in their respective buildings, associated with the increased build up and slower dispersion of internally generated VOCs – with the top floor office space also potentially showing increased concentrations due to build up from other zones and the internal stack airflows. The hospital then offers a contrasting picture. Despite very low CO_2 levels and high ventilation rates, frequent internal sources of VOCs within the hospital setting resulted in significantly higher TVOC concentrations than in the other building types and above guideline associated with sensory irritations (300 $\mu g/m^3$ or 131 ppb) (57)

Figure 3, reports the measured $PM_{2.5}$ concentrations across all buildings. Inside the hospital case study, with F9 filters and with hard, clean surfaces throughout, $PM_{2.5}$ concentrations are just a fraction of outdoor levels. The mean indoor-outdoor ratio (I-O) for the hospital ward rooms is just 0.16 whilst mean indoor levels themselves are just 1.3 $\mu g/m^3$ (median = 0.6 $\mu g/m^3$) – a value at the lower end of those reported in two reviews of experimentally measured I-O ratios (58,59). This is despite median outdoor concentrations of 7.2 $\mu g/m^3$. Lower specification filters (F7) and a hybrid ventilation system at the school resulted in an I-O ratio of 0.35 and median internal concentrations of 2.2 $\mu g/m^3$ (7.3 $\mu g/m^3$ ambient). The naturally ventilated office then had the highest I-O ratio (0.69) and highest median indoor concentrations (3.7 $\mu g/m^3$), despite lower ambient concentrations (5.4 $\mu g/m^3$) across the monitored period.

Finally, Figure 4 demonstrates the measured levels of NO_2 across the case study buildings and their respective zones. Again, the results indicate the influence of building operation and ventilation strategy. The absence of any NOx filtration, such as activated carbon filters or other filters that enact a chemical reaction to filter out NO_2, and higher ventilation rates mean that, conversely to $PM_{2.5}$ levels, the hospital and school have the highest I-O ratios for NO_2 (Hospital: 0.60 or 0.74 within core hours, Office: 0.45, School: 0.67). Whilst internal concentrations are below WHO guidelines for outdoor annual concentrations (21 ppb) in all cases, these trends indicate the influence of the ventilation strategy upon internal concentrations of NO_2 and highlight risks for highly ventilated, unfiltered buildings in high NOx areas, particularly hospitals with vulnerable occupants.

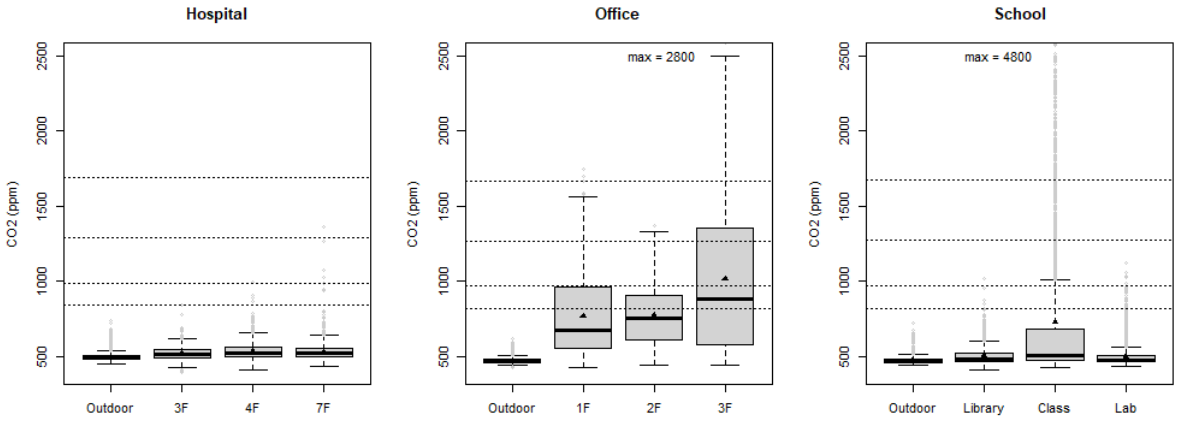


Figure 1: Results of CO_2 monitoring in three case study buildings. (Hourly data). Thresholds for indoor CO_2 concentrations above ambient by +350, +500, +800 and +1,200 ppm, representing IDA classes 1-4 (BS EN 13779:2007)

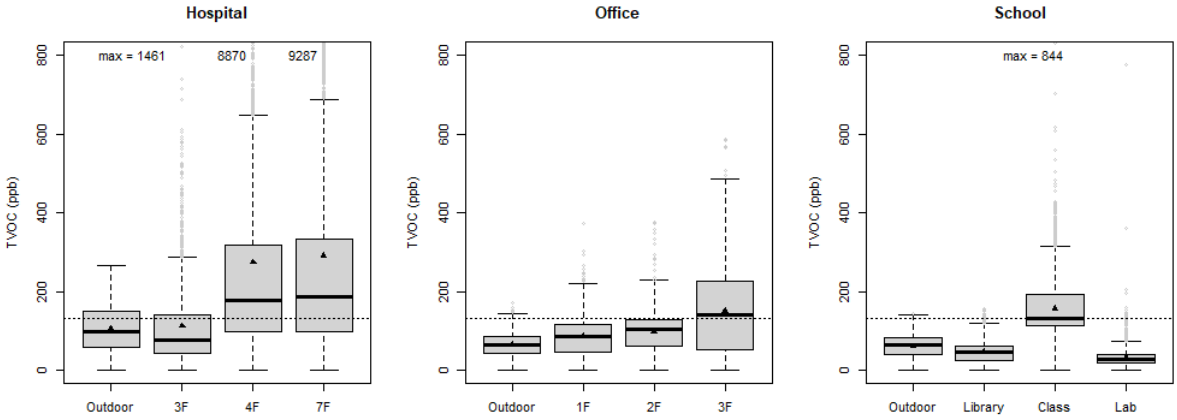


Figure 2: Results of TVOC monitoring in three case study buildings. (Hourly data). UK Part F 8-hour limit for TVOCs is indicated (300 µg/m^3 or 131ppb based upon isobutylene calibrated sensor).

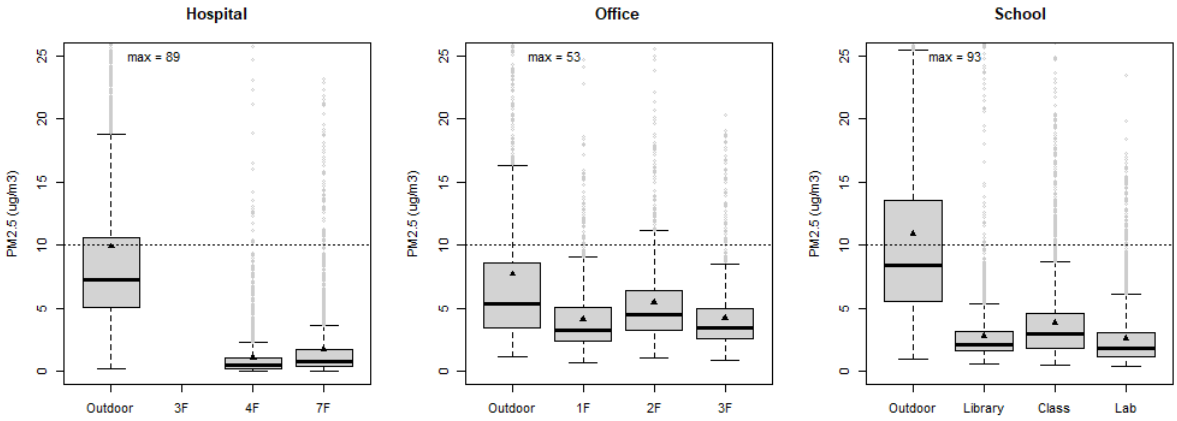


Figure 3: Results of $PM_{2.5}$ monitoring in three case study buildings. (Hourly data). Note one hospital zone (3F) did not record any particulate data. WHO Annual mean limit of 10 µg/m^3 is indicated.

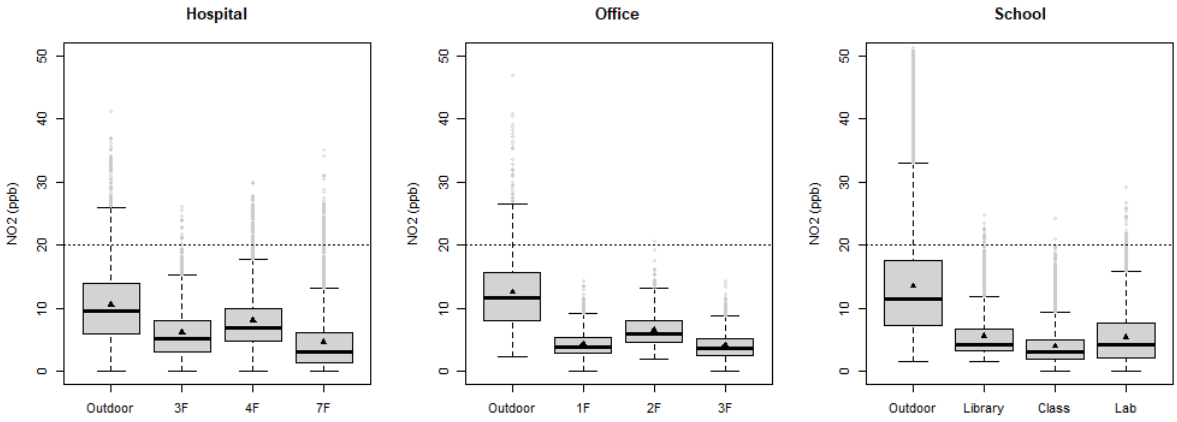


Figure 4: Results of NO_2 monitoring in three case study buildings. (Hourly data). WHO Annual mean limit of 40 µg/m^3 or 21 ppb is indicated.

3.2 Passive sampling and comparisons to ELVs

Summary statistics for passive sampling measurements for NO_2, O_3, formaldehyde and targeted VOCs can be found in Table 3. These results combine measurements from all zones in both the heating and non-heating seasons, with seasonal variations explored later in this paper.

Overall, indoor concentrations are found to be significantly below guideline values for most pollutants across the three buildings. However, all measured formaldehyde levels within the office case study exceeded the guideline of 10 µg/m^3 adopted by Public Health England (54,60), with a maximum over 2.5 times this value . These results indicate that significant off-gassing may still be occurring three years after completion and that existing labelling schemes, guidance and regulation may not be conducive to reaching this target.

Measurements of benzene have proven methodologically problematic, as the limit of detection (LoD) represents a high proportion of the measured values and given no level of Benzene are regarded as ‘safe’ (12). However, measurements above the LoD all significantly exceeded the 0.2 µg/m^3 guideline adopted as best practice for residential dwellings by IEA-ECB Annex 68 (52). Higher external concentrations indicating these are primarily external, traffic related sources.

Mean NO_2 concentrations are around half WHO Guidelines of 21 ppb (40 µg/m^3) for the city-based hospital and school and around half this again in the town-based office. These results approximate those carried out via continuous measurements (Figure 4) although in general comparisons with the continuous time-based monitoring can be problematic. Comparability can be impacted by the measurement methods and their respective uncertainties but also by the fundamental differences in the methods. Diffusive sampling of NO_2 levels typically requires a minimum sampling time of days to weeks. This means that within a school the passive measurement is likely to cover more time outside of normal operating conditions than within it. This limitation becomes particularly important given the variations in time seen later within this paper.

Notably, despite the hospital reporting significantly higher TVOCs, the hospital does not record higher levels in these targeted VOCs. This again highlights methodological difficulties, with both the limitations of the aggregated TVOC measurement and of targeting a relatively small range of specific VOCs.

Measured concentrations reported here can be compared to previous studies to provide some further context. Indoor concentrations of benzene reported here correspond with mean concentrations from previous studies, ranging between 0.98-5.5 µg/m^3, at concentrations that represent risks to occupant health (14,26,29,60,61). Similarly, measured concentrations of formaldehyde in schools and offices have been found to regularly exceeded 10 µg/m^3 guidelines (13,14,26,29,62), with reported ranges extending between 1-66 µg/m^3. As such, measurements from the case study office represents fairly typical concentrations, whilst the school falls at the lower end of previous measurements. Measurements of alpha-pinene and d-limonene from the office case study building, whilst still significantly below guideline values, were higher than maximum concentrations recorded within the OFFICAIR study, although not exceeding those found within the AIRMEX study of public buildings and schools, or measurements taken in domestic settings (26,61).

Further measured VOCs were reported at concentrations significantly below guideline values and correspond to the levels found in previous studies (60).

Table 3: Summary statistics from passive sampling. Guideline exposure limit values (ELV) are given for each pollutant, based upon either WHO / Public Health England Guidance, or upon ELVs from IEA-Annex 68. In units of µg/m^3 unless stated otherwise.

Case Study		**NO_2**	**O_3**	**Formaldehyde**	**Benzene**	**Toluene**
ELV		21 (ppb)	100 (8h)	10	No Safe Level	2,300
Source (12)/(54)		*WHO*	*WHO*	PHE	WHO/ PHE	PHE
Annex 68 Best Practice ELV (52)		10.5 (ppb)	100 (8h)	9	0.2	250
Source		*France*	*WHO*	*USA*	*France*	*Portugal*
Hospital (n=18)	*Mean*	20.4	13.8	4.0	0.80	1.73
	Median	20.3	14.0	3.75	0.80	2.05
	Max	30.2	18.2	6.3	0.95	2.50
	Min	10.6	9.5	2.7	0.65*	0.45*
	<LoD	0.0	0.0	0.0	6	2
Office (n=18)	*Mean*	11.3	14.0	16.4	1.18	2.52
	Median	10.7	7.2	14.4	0.95	2.35
	Max	15.0	48.8	27.1	2.30	4.40
	Min	8.5	2.7*	10.3	0.95*	0.80*
	<LoD	0.0	3.0	0.0	5	1
School (n=18)	*Mean*	22.1	11.1	3.5	1.40	1.62
	Median	20.4	5.63	0.9	0.95	1.20
	Max	42.9	31.4	12.9	2.50	3.50
	Min	11.3	4.6	0.6*	0.95*	0.80*
	<LoD	0.0	0.0	3.0	4	3

Case Study		**T3CE**	**T4CE**	**Styrene**	**Naphthalene**	**d-limonene**	**α-pinene**
ELV		No safe	40	850	3.0	9000	4500
Source (12)/(54)		PHE	PHE	PHE	PHE	PHE	PHE
Annex 68 Best Practice ELV (52)		100	30	30	2	2000	200
Source		*Germany*	*Germany*	*Germany*	*Germany*	*Germany*	*Germany*
Hospital (n=18)	*Mean*	0.35	0.43	0.40	0.38	14.3	3.8
	Median	0.35	0.45	0.40	0.40	14.9	4.2
	Max	0.45	0.55	0.50	0.60	23.7	7.8
	Min	0.25*	0.30*	0.30*	0.25*	2.9*	0.7*
	<LoD	6	6	6	5	1.0	4.0
Office (n=18)	*Mean*	0.46	0.56	1.50	0.40	44.8	136.3
	Median	0.45	0.55	1.80	0.40	46.7	129.9
	Max	0.50	0.60	2.60	0.40	87.8	286.4
	Min	0.45*	0.55*	0.50*	0.40*	2.9*	9.5
	<LoD	6	6	2	6	3.0	0.0
School (n=18)	*Mean*	0.45	0.55	1.75	0.50	3.3	5.6
	Median	0.45	0.55	0.85	0.40	3.3	5.1
	Max	0.45	0.55	4.20	1.00	3.6	9.9
	Min	0.45*	0.55*	0.50*	0.40*	2.9*	0.7*

<LoD	6	6	4	5	6.0	3.0

* Indicates reported measurements were below the limit of detection (<LoD).

3.3 Top 5 VOCs

The 'top 5' VOCs were recorded at each measurement location across both the heating and non-heating seasons. This qualitative method cannot accurately determine the concentration of these VOCs but rather identifies those with the highest concentrations across the measurement period, gaining a broader understanding of the pollutants present.

The hospital, with regular peaks in continuously measured TVOCs, perhaps unsurprisingly identifies isopropyl alcohol (found in cleaning swabs, hand gels etc.) as the top VOC in each location, consistent with frequent peaks associated with cleaning from the continuous monitoring. Limonene and alpha-pinene (again associated with cleaning products) are the most commonly seen VOCs within the office environment, corresponding to the quantitative analysis in Table 3, although these remain significant below guidelines values. Finally, cyclopentane, with known health risks (63), is found in a number of locations within the school building and likely to be associated with the phenolic foam insulation, whilst the second most commonly occurring pollutant, cyclohexadecane is associated with diesel fuel additives and outdoor traffic.

3.4 Seasonal trends in outdoor sources of pollutants

The ingress of external pollutants to the internal environment is a function of both penetration through infiltration and the ventilation air change rate of the building. In a naturally ventilated building, this means that the use of ventilation openings can have a significant impact upon the proportion of external pollutants found indoors. Outdoor concentrations during the non-heating season (May-Aug) are almost half those during the heating season, although a similar reduction is not observed in indoor levels.

To explain this result, Figure 5 shows the changing indoor outdoor (I-O) ratio across the monitored period, along with average monthly CO_2 concentrations. Internal CO_2 concentrations drop significantly as increasing external air temperatures both allows and increases the need for increased ventilation. However, this increased ventilation rate itself increases the I-O ratio and the proportion of external NO_2 entering internal spaces, resulting in as high concentrations of NO_2 in the summer as the winter period. I-O ratios measured through diffusive sampling (Table 4) then show similar increases between the summer and winter seasons (0.82 Summer – 0.55 Winter). These results indicate the influence of ventilation rates, strategy and occupant actions upon IAQ.

Results for seasonal changes in I-O ratios for NO_2, $PM_{2.5}$ and PM_{10} are shown for all buildings in Table 5. Season changes in I-O ratios for NO_2 can be seen in all buildings, although most significantly in the school and office, which both see the highest seasonal changes in CO_2 concentrations. Similarly, I-O ratios for $PM_{2.5}$ are seen to increase in the summer in the school and summer buildings, by around 50% in both cases. Importantly, reported ranges for all pollutants show significant variations between individual days, indicating further underlying factors affecting these relationships.

Seasonal trends may then be clearer observed against external temperature Figure 6. Both buildings with openable windows show an increase in I-O for NO_2 as outdoor temperatures increase, following models of window opening behavior (61) and as observed in other studies with increased summertime natural ventilation (64). It is also notable that the variation in I-O ratio also increases with increasing external temperature, indicated a more varied relationship between indoor and outdoor air. The sealed hospital shows somewhat different behavior, with significant variation across all temperatures and less pronounced relationship with external temperature.

In all cases, trends with particulates are more complex, with internal sources or resuspension resulting in a less direct relationship between indoor and outdoor environments and the I-O a more limited description of these processes (58). None of the case study buildings demonstrate any clear

seasonal patterns in particulates, although there again remain significant variations between months and individual days.

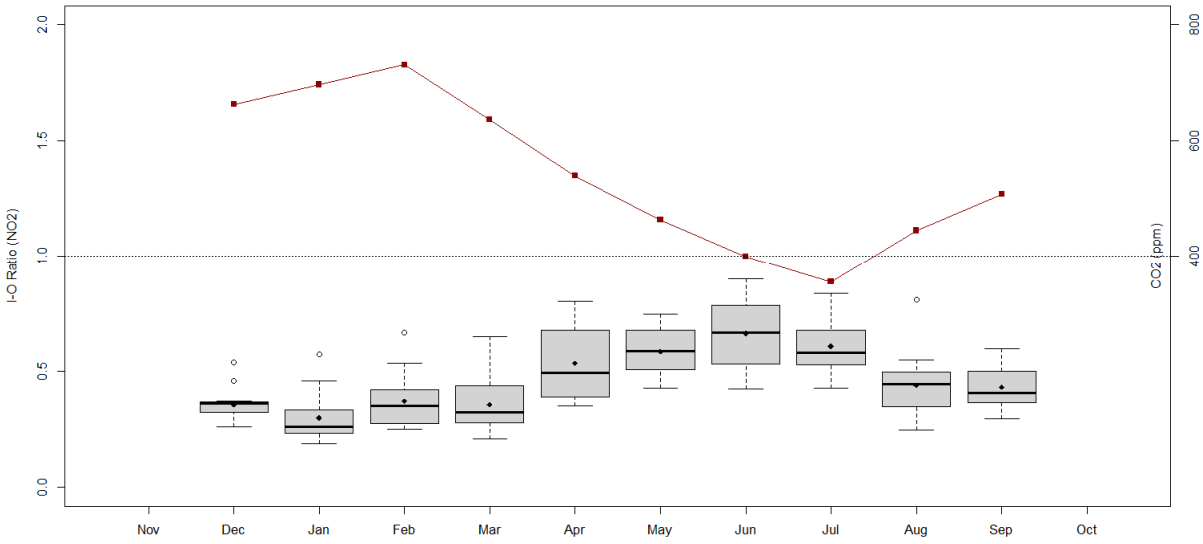


Figure 5: Monthly boxplots showing daily I-O ratios within the office building and mean monthly internal CO_2 concentration.

Table 4: Indoor outdoor ratios from passive sampling measurements.

		NO_2		O_3	
		Summer	Winter	Summer	Winter
Hospital	3rd Floor	0.97	0.76	0.36	0.24
	4th Floor	1.01	0.80	0.41	0.30
	7th Floor	1.12	0.80	0.36	0.28
	Mean	**1.03**	**0.79**	**0.38**	**0.27**
Office	1st Floor	0.94	0.58	0.24	<LoD
	2nd Floor	0.71	0.65	0.32	<LoD
	3rd Floor	0.81	0.44	0.41	<LoD
	Mean	**0.82**	**0.55**	**0.32**	<LoD
School	Classroom	0.85	0.88	0.44	0.25
	Lab	0.64	0.48	0.08	0.09
	Library	0.55	0.50	0.06	0.09
	Mean	**0.68**	**0.62**	**0.19**	**0.14**

Table 5: Seasonal variation in I-O ratios and CO_2 concentrations for the all buildings. The heating season is Dec – Mar inclusive. Non-heating season Apr – Sep Inclusive. I-O ratios are reported as median, daily ratio, with interquartile range provided alongside. Data is based upon occupied hours only.

		CO_2 (ppb)	NO_2 (IQR)	$PM_{2.5}$ (IQR)	PM_{10} (IQR)
Hospital	Heating Season	556	0.65 (0.43)	0.10 (0.14)	0.25 (0.25)
	Non-Heating Season	559	0.83 (0.52)	0.10 (0.15)	0.32 (0.41)
Office	Heating Season	1068	0.28 (0.21)	0.51 (0.21)	1.02 (0.48)

	Non-Heating Season	667	0.54 (0.28)	0.77 (0.24)	1.01 (0.35)
School	Heating Season	876	0.59 (0.28)	0.24 (0.18)	0.55 (0.38)
	Non-Heating Season	667	0.90 (0.49)	0.36 (0.30)	0.56 (0.53)

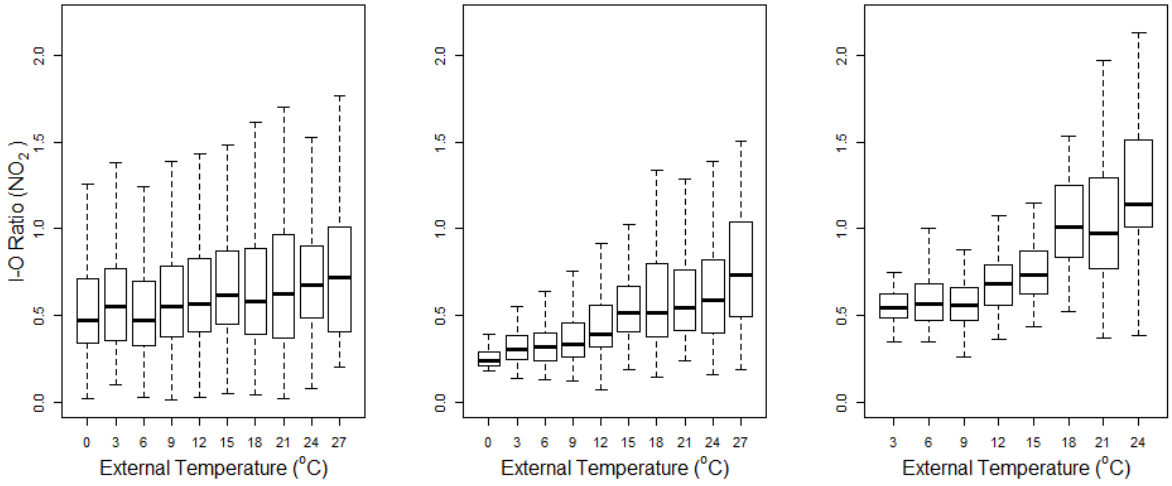


Figure 6: I -O ratio for NO_2 against external temperature, for hospital (left), office (middle) and school (left). Data is binned into boxplots of 3°C intervals, based upon hourly data.

3.5 Seasonal trends in indoor sources

This relationship between increased ventilation and higher ingress of NO_2 can similarly be observed in Figure 7. Here, the inverse relationship between CO_2 levels and NO_2 contrasts with the positive corrrelation seen between TVOCs and CO_2. Taking CO_2 as a proxy for ventilation rates, increased natural ventilation helps to dilute internally generated TVOCs but at the same time increases ingress and internal NO_2 concentrations. This further demonstrates the limitations of CO_2 as a proxy for air quality and the sole use of CO_2 sensors within a ventilation control strategy, particularly when there is a risk of bringing in unfiltered, polluted external air. Seasonal differences in internal sources can also be assessed through the results of passive sampling. In the naturally ventilated office, significant reductions are seen from the winter to the summer in formaldehyde (21.6 – 11.2 µg/m^3), d-limonene (67 – 23 µg/m^3) and alpha-pinene (199 – 74 µg/m^3). Previous studies of offices and public buildings (26,62) have found higher summertime concentrations of formaldhyde, linking higher temperatures to increased off-gassing. Here, however, the indication is that any increase if off-

gassing is more than offset by the increased ventilation rate and higher rate of dilution. In the other case study buildings, some smaller scale reductions can be seen in both d-limonene and alpha-pinene, although not in other of pollutants.

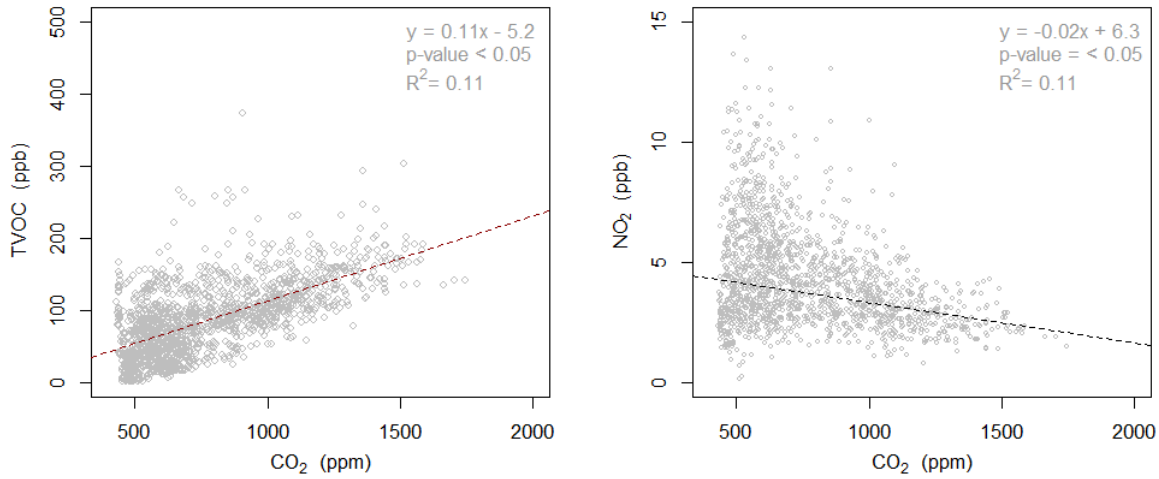


Figure 7: Correlation between CO_2 and both NO_2 and TVOCs. 1st Floor Office Building. Hourly data. Working hours only.

3.6 Daily variations

Through continuous IAQ monitoring, the relationship between ventilation rates and I-O ratios can similarly be explored in the context of aggregated daily ventilation schedules. In the hospital case study (Figure 8), indoor CO_2 concentrations begin to increase around 06:00, initially reducing from around 15:00 onwards, before further reductions beyond 19:00. This follows typical schedules within the wards and the CO_2 based demand-controlled ventilation would be expected to follow a similar profile. Examining the aggregated daily NO_2 profiles reveals two outdoor peaks, associated with peaks in traffic at occurring around 06:00-09:00 in the morning and a larger evening peak, reaching a maximum between 19:00-20:00.

These timings play an important role on the relationship between indoor and outdoor NO_2 concentrations. The morning peak in outdoor concentrations is mirrored by indoor levels, albeit with a lag of approximately 1 hour (mean I-O ratio = 0.84). However, the stronger evening peaks reveal a much more subdued response from internal levels (mean I-O ratio = 0.46). This can be explained by

the increased ventilation rates expected during the morning peak (within core occupied hours) compared to the lower expected air change rate in the evening. Whilst indoor NO_2 concentrations show a strong correlation with external levels, the influence of the building operation and delivered ventilation rates during hours of peak traffic is clear.

Importantly, a similar response is not seen in indoor particulate levels as a result of the high level of filtration. These results again indicate the potential need for NOx filters within buildings in high NOx zones, particularly for buildings operating with high air exchange rates. This would increase both cost and space requirements, a simpler strategy may be to reduce ventilation requirements during known peak traffic hours and strike a balance between outdoor pollution and CO_2 levels. The results here demonstrate demand-controlled ventilation only based on CO_2, may not sufficiently provide and maintain acceptable IAQ where there are major sources of pollution outdoors.

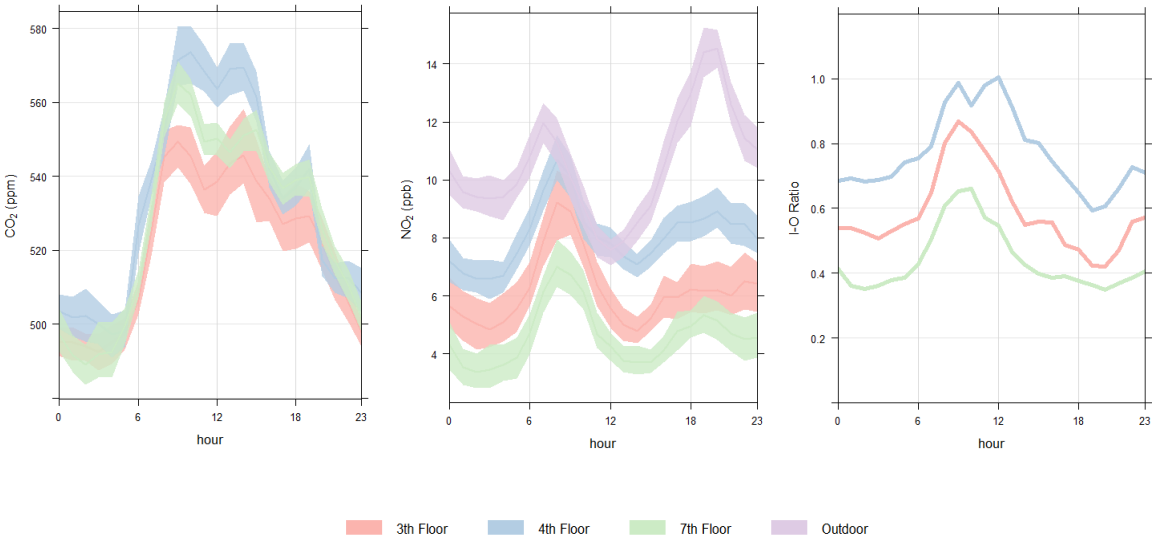


Figure 8: Daily variation in CO2 (left), NO2 (centre) and NO2 I-O ratio (right) for hospital case study. Typical profiles are based on aggregated days across entire dataset.

Equivalent plots can be seen for the school (Figure 9) and office (Figure 10) buildings. Within the mechanically ventilated school, dual external traffic peaks are again followed by peaks internal concentrations. Comparably to the hospital case study, the response to this evening peak is more muted, with I-O ratios peaking around midday. The classroom, with a faulty CO_2 sensor and lower

delivered ventilation rates, then has lower NO_2 levels and I-O ratio which may relate to less air being brought into the space.

The naturally ventilated office displays somewhat different behavior. Responses to external traffic peaks are less pronounced, with a more general build up in internal concentrations seen across the day. As a result, I-O ratios are more consistent, with the highest values seen overnight between the end and start of working hours. This behavior is seen more clearly in the winter months, so it is expected to be associated with lag between indoor and outdoor levels and the slower rate of dispersion seen indoors, rather than the result of any night-time summer ventilation strategy. Such behavior has also been seen in commercial properties (40).

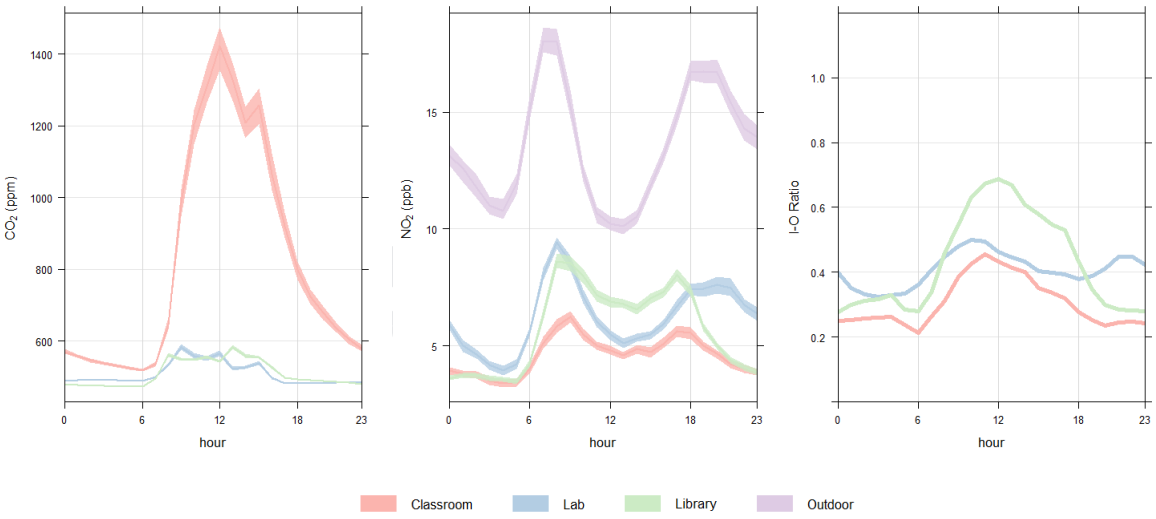


Figure 9: Daily variation in CO2 (left), NO2 (centre) and NO2 I-O ratio (right) for hospital case study. Typical profiles are based on aggregated days across entire dataset.

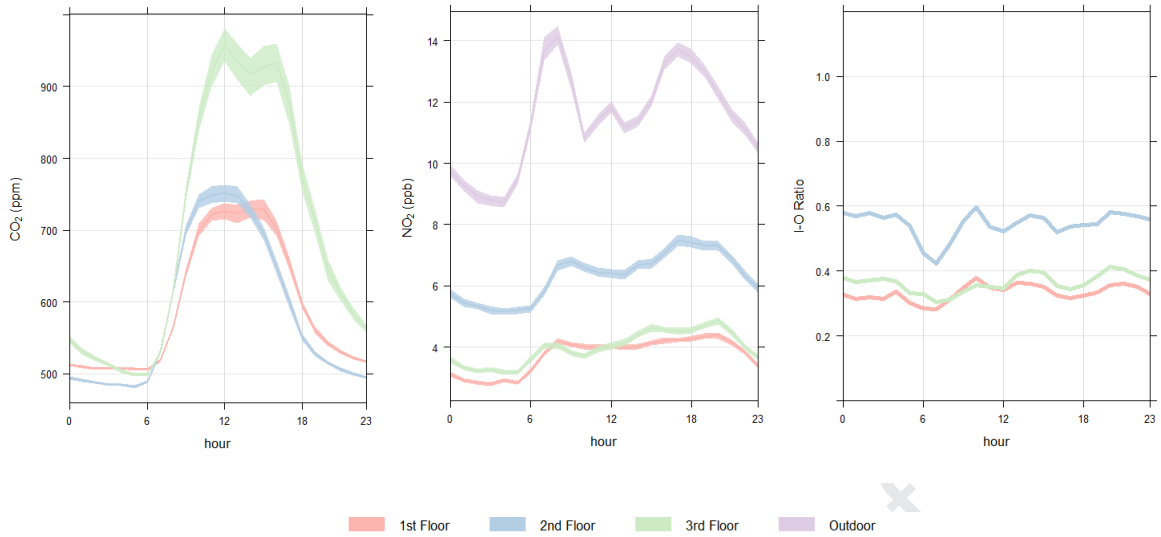


Figure 10: Daily variation in CO2 (left), NO2 (centre) and NO2 I-O ratio (right) for hospital case study. Typical profiles are based on aggregated days across entire dataset.

Conclusion

Continuous air quality measurements have been taken in three case study buildings in heating and non-heating seasons, over periods of 6-10 months. Combined with shorter-term, passive sampling of targeted key pollutants, these continuous measurements provided valuable dynamic information upon the relationship between IAQ and building operation.

Operationally, in a naturally ventilated office case study, increased summertime ventilation led to a reduction in indoor generated pollutants – with concentrations of formaldehyde, d-limonene and alpha-pinene all reducing by more than half. However, increased ventilation rates also led to a significant increase in the I-O ratio of NO_2, with monthly means ranging from 0.30 in the winter to 0.66 in the summer. This resulted in higher indoor concentrations of NO_2 in the summer than the winter, despite the significant reductions in summertime outdoor concentrations. This case study therefore highlights the role of seasonal ventilation practices, occupant behaviour and their influence upon IAQ.

Even with increased summertime ventilation rates, and measurements taking place 3 years post completion, all formaldehyde measurements in the office exceeded the IEA Annex 58 ELV (9 µg/m^3).

This not only demonstrates the difficulties in balancing the dilution of indoor with the ingress of outdoor pollutants, but also highlights the importance of source control for indoor generated pollutants, particularly VOCs, within building specifications and operation, a challenge given current labelling deficiencies (65). UK regulation previously only specified guidance based upon TVOC concentrations (57). Given the associated health risks, clearer labelling and guidance are likely to be required to meet the more recently introduced Public Health England guidelines for formaldehyde (10 $\mu g/m^3$), particularly in naturally ventilation buildings such as this, where lower ventilation rates in the winter led to levels over double this guideline (21.6 $\mu g/m^3$).

Mechanically ventilated case studies, a school and hospital, showed effective particulate filtration. However, in the absence of any NOx filtration, high ventilation rates result in a high ingress of outdoor NO_2, with the hospital case study having the lowest I-O ratio for particulates (0.17) but the highest for NO_2 (0.60 or 0.74 in core hours). These ratios can be seen to change across a given day, with higher proportions of external NO_2 brought into the building during core occupied hours, where higher CO_2 levels and demand control ventilation increased the ingress of NO_2. Practically, these results show the need for NOx filtration, particularly in polluted zones and where high ventilation rates will be targeted. Further, these results demonstrate the limits of demand control ventilation systems based solely upon CO_2, along with the impact of scheduling high ventilation rates during peak traffic hours. Results from both mechanically and naturally ventilated buildings have indicated how I-O ratios may need to be assessed across a day and seasons to better understand variations in IAQ and links to building operation.

Finally, methodologically, low-cost, continuous air quality sensing, has been shown to yield valuable dynamic information upon the relationship between IAQ and both building operation and external environmental conditions. Variation seen here on a seasonal to hourly basis, indicate limitations in aggregated, diffusive sampling methods, both in terms of the information provided and the representativeness of measurements. Developments in sensing technologies, along with suitable

quality assurance processes, mean there is potential for wider adoption of long-term continuous monitoring. There is potential for such approaches to provide detailed understanding of IAQ and strategies to minimise concentrations of pollutants on an individual building scale.

Appendix A – Sensor performance and quality assurance

This section of the appendix reports further details on the results from co-location tests with reference instruments and inter-sensor comparisons. Details of the sensors used within the integrated air quality sensor can be found in Table A1, alongside comparisons to reference instruments and inter-sensor comparisons. Here comparisons with reference instruments are reported in terms of the average root mean square error (RMSE), mean bias error (MBE) and range in correlation coefficients (R^2) as recommended by a review by the Joint Research Council (53).

Nitrogen Dioxide Sensor Performance

Results indicate good level of agreement with reference instruments and with inter-sensor comparisons. Performance against NO_2 reference instruments (RMSE = 3.5 ppb and R^2 = 0.69-0.81) corresponds to those from assessments by Chatzidiakou, et al., (43) (R^2 > 0.84, RMSE <3 ppb) and Mead et al., (66), where the limit of detection (LoD) was estimated to be <4 ppb. Inter-sensor comparisons then show a high level of aggregability with a minimum R^2 > 0.89 and a coefficient of variation (CV) of 7% - lower than the 10% prescribed for indicative measurements (67).

Results from NO_2 sensors co-located with reference instruments can be seen FigureA1, demonstrating good agreeability across this period. For field deployments, comparisons can be made to nearby, permanent, air quality stations, 1 km and 2.7 km away from the case study buildings respectively (46,47). External NO_2 measurements at the hospital (FigureA3 - A6) and school (Figure A711A7- A10) can be compared to local permanent stations. Good agreement is seen across the overall timeseries and within daily, weekly and monthly aggregated patterns. Despite expected spatial variation, this provides a useful check on measured levels and changes in sensor offsets and sensitivities across the monitoring campaign.

Particulate Sensor Performance

Particulate data shows reasonable agreement with reference instruments at low concentrations (<12 μg/m^3 – R^2 = 0.58-0.77, RMSE = 2.1 μg/m^3) but at higher concentrations, periods of high humidity need to be filtered out in order to see good agreement (R^2 = 0.75-0.86, RMSE = 6.8 μg/m^3). Coefficients of variation are then around 15% across both these ranges. Studies of sensor Alpha sense OPC-N2 particulate sensors have reported significant variations based upon the treatment of particulate data. Chatzidiakou, et al., (2019), report good performance against reference instruments (R^2 = 0.8, RMSE = 2 μg/m^3) when corrections for RH and scaling factors are applied, but a lower agreement when these RH corrections could not be applied (R^2 >0.57; RMSE = 9 μg/m^3). Sousan 2016, echo these results with RH corrections significantly improving both R^2 (0.34 – 0.75) and RMSE (36 – 6 μg/m3). Within this paper, particulate data is filtered, removing periods of high humidity (85%) to avoid bias, resulting in an R^2 = 0.75-0.86 and RMSE = 6.8 μg/m^3 compared to reference instruments – an approach found to be effective in a broader review of low-cost sensors (68). However, unlike NO_2 measurements, particulate data is not corrected based upon reference measurements. Jiang et al.,(2011) demonstrated that a TSI Sidepack, real-time monitor, overestimated gravimetric measurements of $PM_{2.5}$ by factors of 0.92–1.8 for outdoor sources, 1.3 for toasting bread, and 3.4 for cigarette smoke. As such, these uncertainties and any applied correction factors are a function of the composition of particulates in which measurements were made (70). For this reason, particulate data is not scaled to reflect the reference instrument, but rather to a collective mean of all sensors to improve inter-sensor reproducibility.

Results from particulate sensors co-located with reference instruments can be seen FigureA1, demonstrating good agreeability across this period when RH filtering has been applied. For field deployments, comparisons can be made to nearby, permanent, air quality stations (46,47). External $PM_{2.5}$ and PM_{1-} measurements at the hospital (FigureA3, A5, A6) and school (Figure A711A7, A9, A10) can be compared to local permanent stations. Generally reasonable agreement is seen across the overall timeseries, with less clear association within daily, weekly and monthly aggregated patterns.

Despite expected spatial variation, again, this provides a useful check on measured levels and changes in sensor offsets and sensitivities across the monitoring campaign.

External sensors from the case study hospital and school have been compared to 3rd part Automatic Urban Rural Network reference stations, 1 km and 2.7 km away from the case study buildings respectively (FigureA3-FigureA10). These demonstrate a good level of agreement with the external sensors deployed at both sites, within the expected spatial variation.

Table A1: Sensor specifications and comparative data.

Variable	Sensor	Method		Comparison to reference instrument (N=4)	Inter-comparison (N=15)
Carbon Dioxide (CO2)	E+E	Non-Dispersive Infra-Red (NDIR)		NA	CV = 2% R^2 > 0.98 RMSE = 11 ppm
Particulate Matter (PM1, PM2.5, PM10)	Alphasense OPC-N2	Optical Particle Counter (OPC) 0.38 – 17um	$PM_{2.5}$ (<12 µg/m3)	R^2 = 0.58-0.77 RMSE = 2.1 µg/m^3 MBE = 0.7 µg/m^3	CV = 14% R^2 =0.92 RMSE = 2.1 µg/m^3 MBE = -0.1 µg/m^3
			$PM_{2.5}$ (<85% RH)	R^2 = 0.75-0.86 RMSE = 6.8 µg/m^3 MBE = 4.0 µg/m^3	CV = 15% R^2 = 0.92 RMSE = 2.4 µg/m^3 MBE = 0.1 µg/m^3
			PM_{10} (ALL)	R^2 = 0.52-0.83 RMSE = 12.6 µg/m^3 MBE = 7.0 µg/m^3	CV = 8% R^2 = 0.52 RMSE = 3.8 µg/m^3 MBE = 0.31 µg/m^3
Nitrogen dioxide (NO2)	Alphasense NO2-A43F	Eltectrochemical		R2 = 0.69-0.81 RMSE = 3.5 ppb MBE = 0.5 ppb	CV = 7% R^2 > 0.89 RMSE = 3.3 ppb MBE = 0.8 ppb
Total Volatile Organic Compounds (TVOCs)	Alphasense PID-AH2	Photoionization detector (PID–Isobutylene)		NA	CV = 24% R^2 > 0.31 Mean = 0.59 RMSE = 29 ppb

* Temperature and relative humidity sensors have stated accuracies of +/- 0.4°C and of +/- 4%. Carbon dioxide of ± (50 ppm) or 3% of measured value).

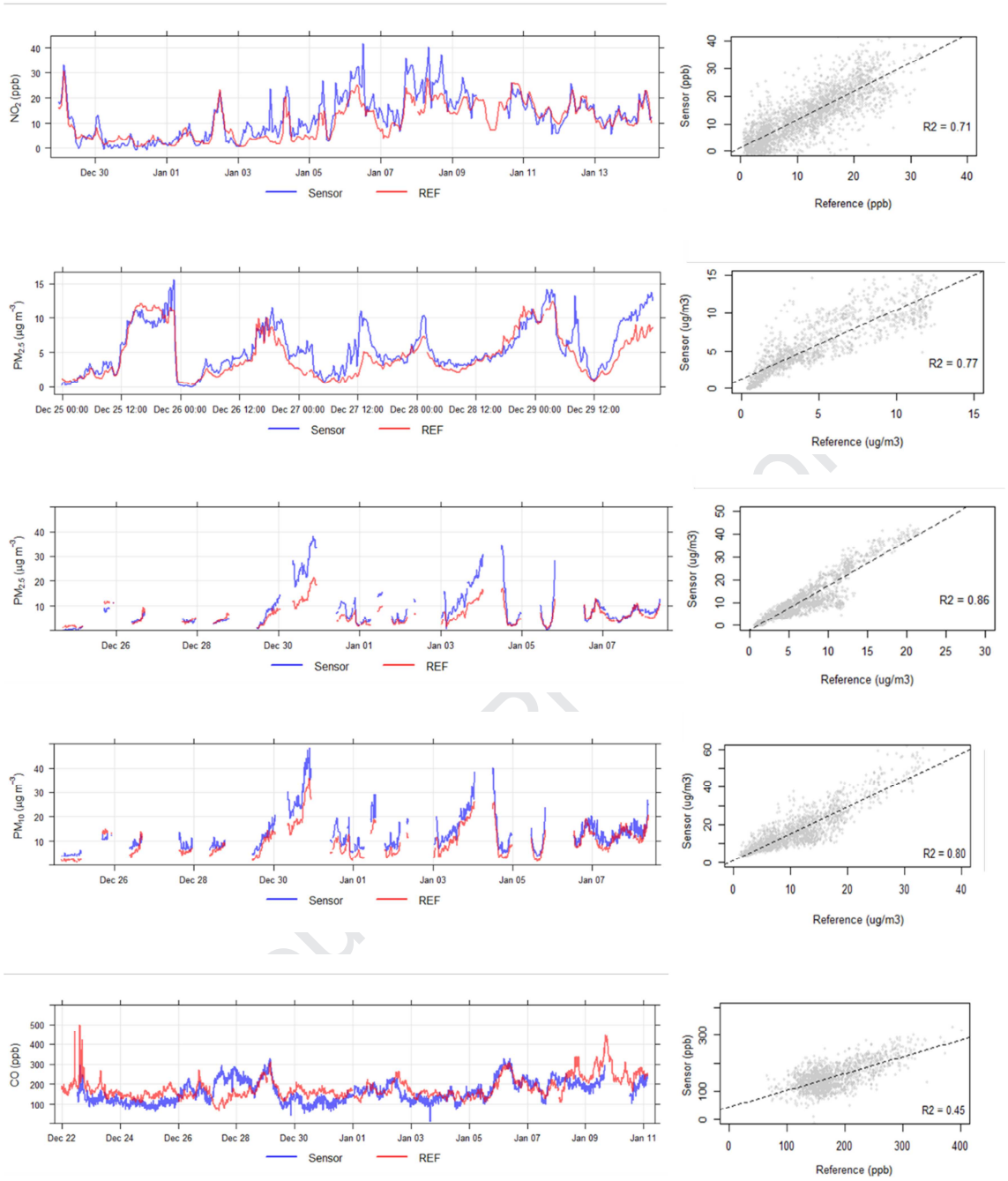


Figure A1: Comparison between corrected sensors and reference instruments. NO_2 (Chemiluminescence, Thermo Fisher Scientific, Model 42i, $PM_{2.5}$, PM_{10} (Aerosol spectrometer FIDAS PALAS 200S), CO (Nondispersive infrared, Thermo Fisher Scientific model 48i).

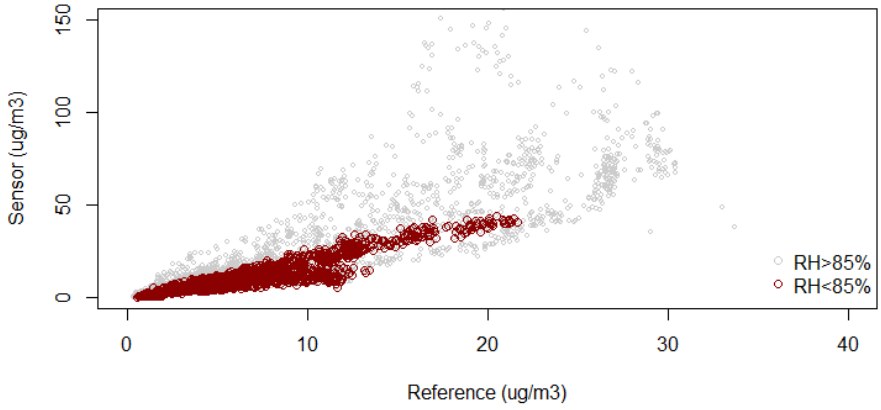


Figure A2: Demonstration of humidity bias in OPC sensors.

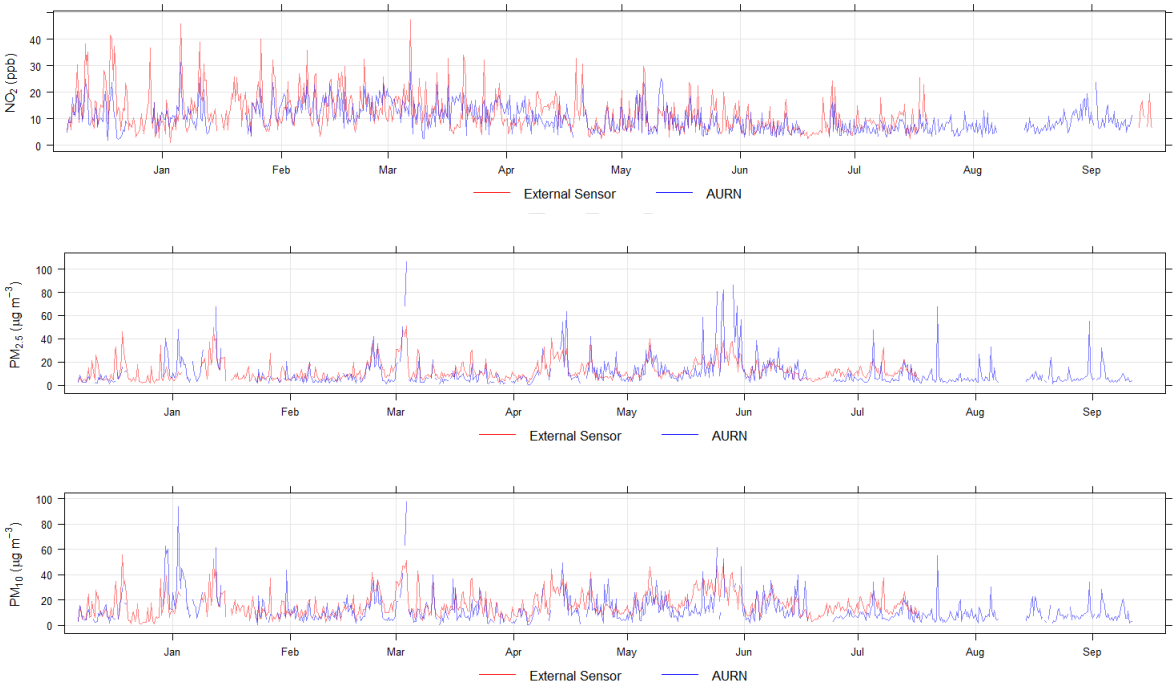


Figure A3: Hospital Case Study. Comparison between external air quality sensor and nearest urban background Automatic Rural Network (AURN) station - Bristol St Pauls.8 hour aggregation. Top) NO_2, Mid) $PM_{2.5}$, Bottom) PM_{10}.

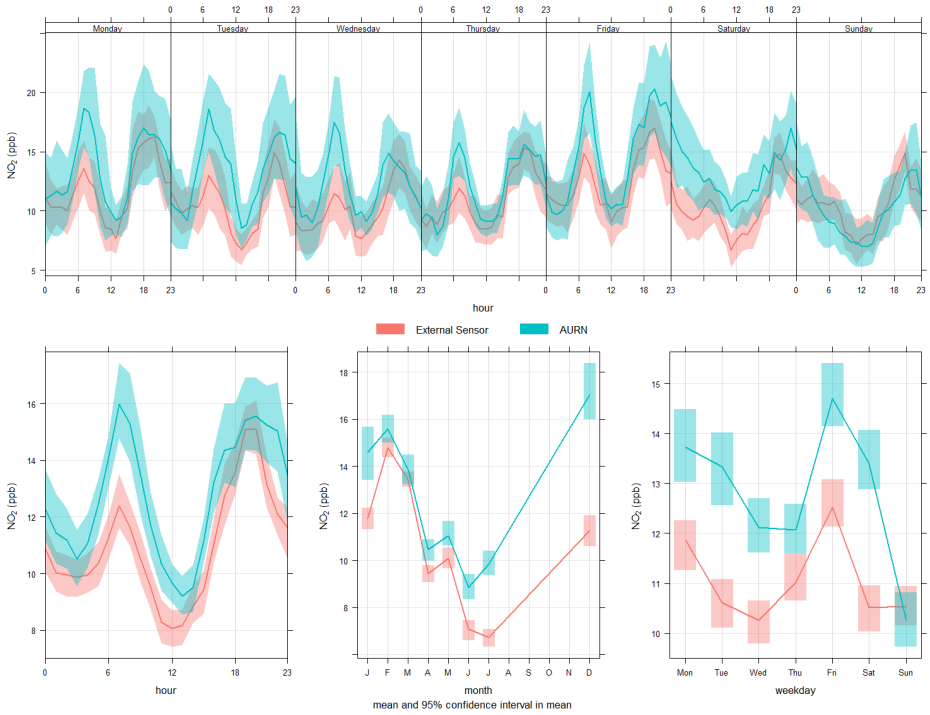


Figure A4: Hospital Case Study. NO_2 comparison between external air quality sensor and nearest urban background Automatic Rural Network (AURN) station. Aggregated daily, weekly, monthly profiles across periods in which both stations recorded data.

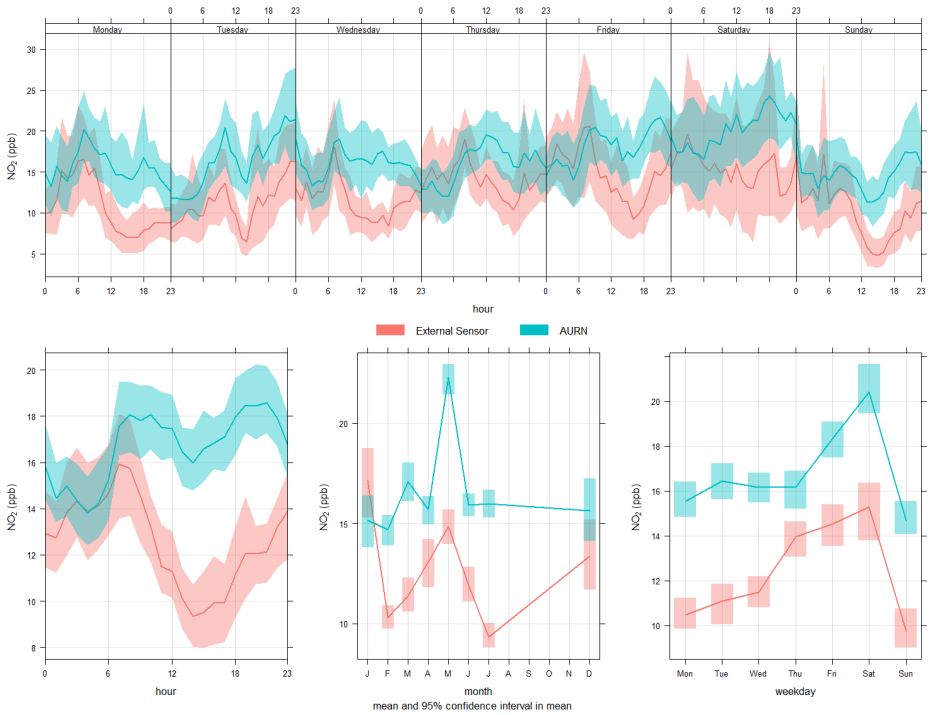


Figure A5: Hospital Case Study. $PM_{2.5}$ comparison between external air quality sensor and nearest urban background Automatic Rural Network (AURN) station. Aggregated daily, weekly, monthly profiles across periods in which both stations recorded data.

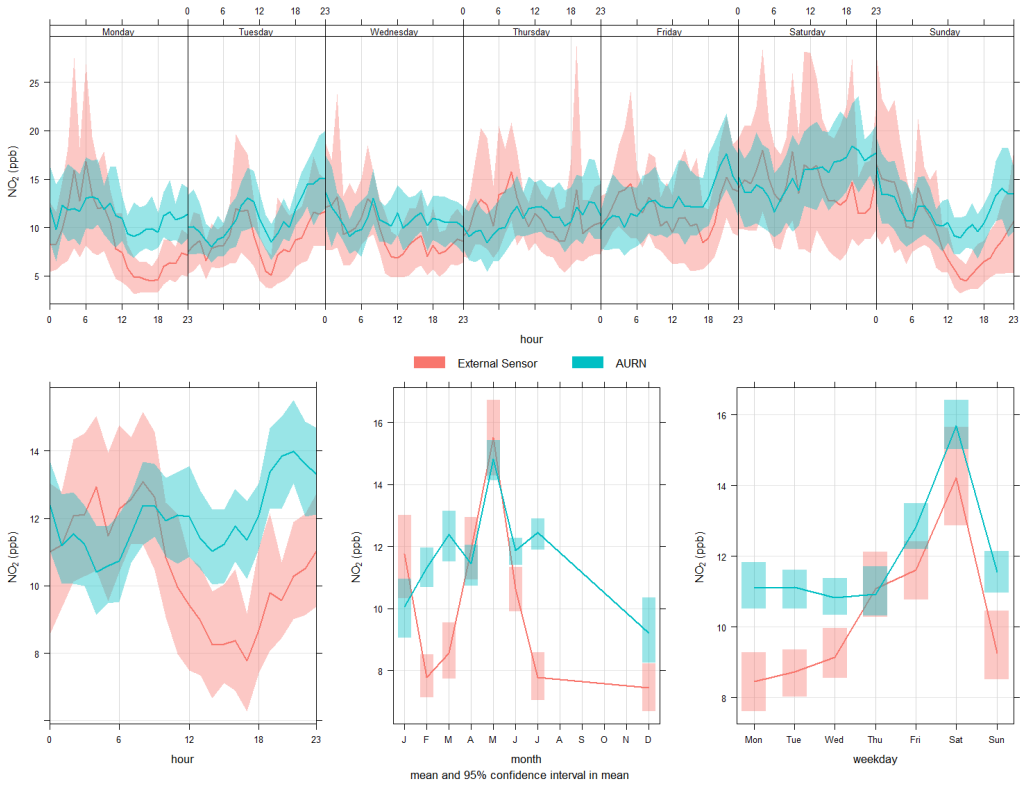


Figure A6: Hospital Case Study. PM_{10} comparison between external air quality sensor and nearest urban background Automatic Rural Network (AURN) station. Aggregated daily, weekly, monthly profiles across periods in which both stations recorded data.

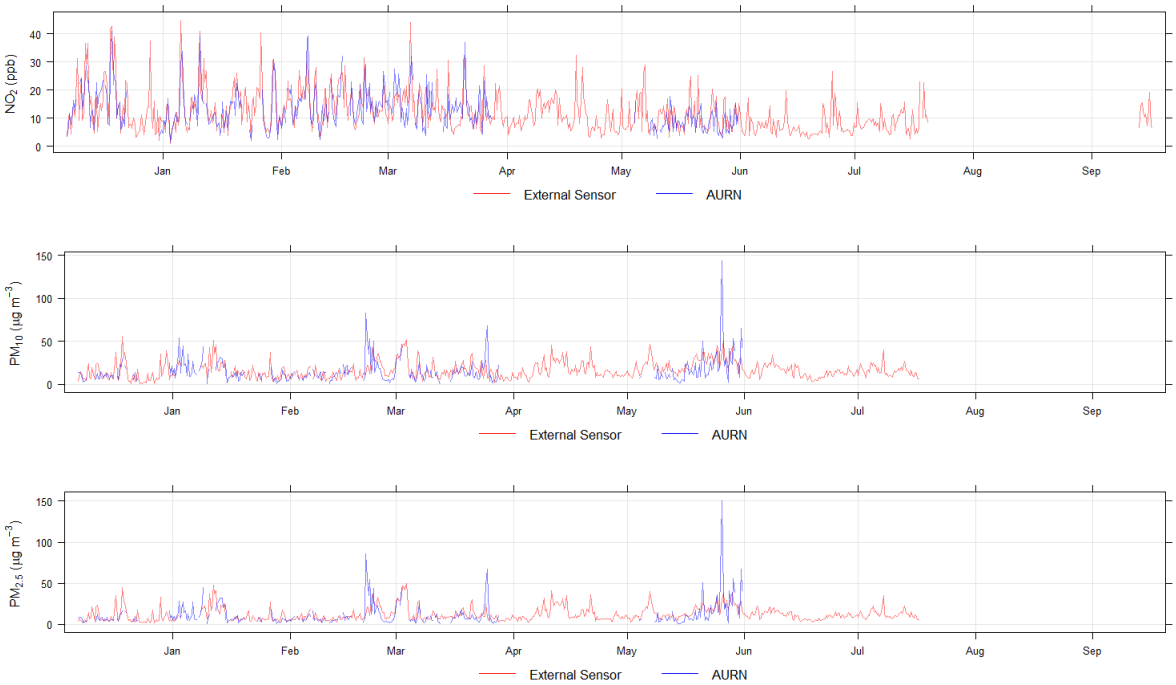


Figure A711: School Case Study. Comparison between external air quality sensor and nearest urban background Automatic Rural Network (AURN) station -.8 hour aggregation. Top) NO_2, Mid) $PM_{2.5}$, Bottom) PM_{10}.

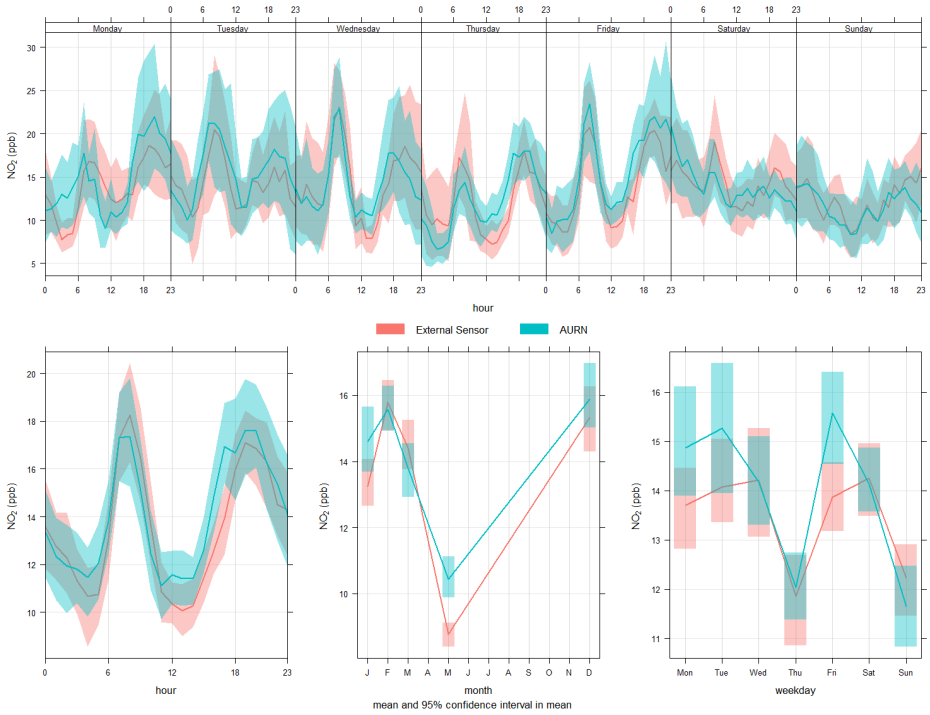


Figure A8: School Case Study. NO_2 comparison between external air quality sensor and nearest urban background Automatic Rural Network (AURN) station. Aggregated daily, weekly, monthly profiles across periods in which both stations recorded data.

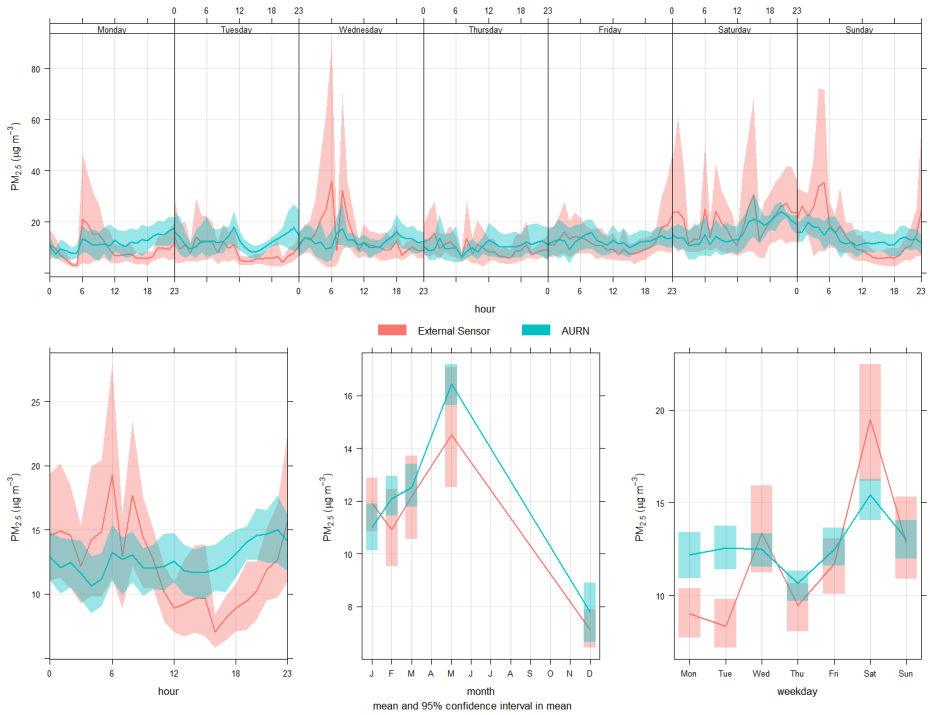


Figure A9: School Case Study. $PM_{2.5}$ comparison between external air quality sensor and nearest urban background Automatic Rural Network (AURN) station. Aggregated daily, weekly, monthly profiles across periods in which both stations recorded data.

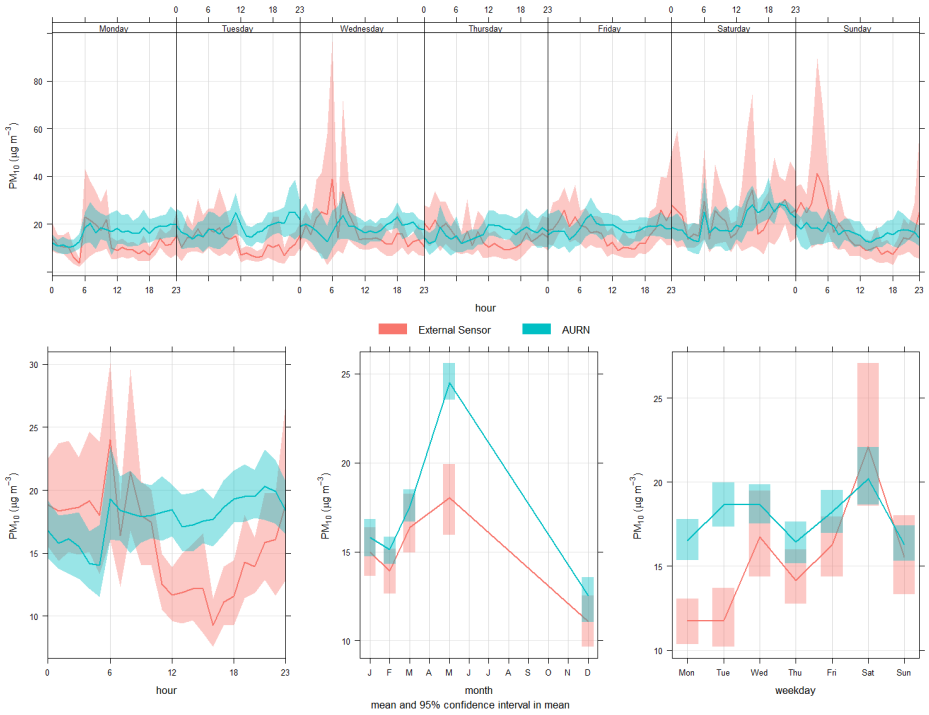


Figure A10: School Case Study. PM_{10} comparison between external air quality sensor and nearest urban background Automatic Rural Network (AURN) station. Aggregated daily, weekly, monthly profiles across periods in which both stations recorded data.

Table A2: Response factors of TVOC sensor to compounds discussed within paper

Compound	Response factor	Minimum detection level (ppb)
Targeted VOCs		
Formaldehyde	No response	-
Benzene	0.5	3
Toluene	0.56	3
Trichloroethylene	0.6	3
Tetrachloroethylene	0.4	4
Styrene	0.45	2
Naphthalene	0.4	2
d-limonene	0.9	6
alpha-pinene	0.34	-
Top 5 VOCs detected		
Cyclopentane	10	-
Acetic Acid	28	180
Decanal	0.9	-
Diethyl phthalate	1	5
Decane	1.2	5
Heptane	2.2	10
Hexanal	1.2	-

References

1. Dockery DW, Pope CA, Xu X, Spengler JD, Ware JH, Fay ME, et al. An Association between Air Pollution and Mortality in Six U.S. Cities. N Engl J Med. 1993 Dec 9;329(24):1753–9.

2. Pope CA. Respiratory disease associated with community air pollution and a steel mill, Utah Valley. Am J Public Health. 1989 May 1;79(5):623–8.

3. Landrigan PJ, Fuller R, Acosta NJR, Adeyi O, Arnold R, Basu N (Nil), et al. The Lancet Commission on pollution and health. The Lancet. 2018 Feb 3;391(10119):462–512.

4. Carey IM, Anderson HR, Atkinson RW, Beevers SD, Cook DG, Strachan DP, et al. Are noise and air pollution related to the incidence of dementia? A cohort study in London, England. BMJ Open. 2018 Sep 1;8(9):e022404.

5. Leiser CL, Hanson HA, Sawyer K, Steenblik J, Al-Dulaimi R, Madsen T, et al. Acute effects of air pollutants on spontaneous pregnancy loss: a case-crossover study. Fertil Steril. 2019 Feb 1;111(2):341–7.

6. Braithwaite I, Zhang S, Kirkbride JB, Osborn DPJ, Hayes JF. Air Pollution (Particulate Matter) Exposure and Associations with Depression, Anxiety, Bipolar, Psychosis and Suicide Risk: A Systematic Review and Meta-Analysis. Environ Health Perspect. 2019;127(12):126002.

7. Schraufnagel DE, Balmes JR, Cowl CT, Matteis SD, Jung S-H, Mortimer K, et al. Air Pollution and Noncommunicable Diseases: A Review by the Forum of International Respiratory Societies' Environmental Committee, Part 2: Air Pollution and Organ Systems. CHEST. 2019 Feb 1;155(2):417–26.

8. WHO. 9 out of 10 people worldwide breathe polluted air, but more countries are taking action [Internet]. 2018 [cited 2020 Jan 30]. Available from: https://www.who.int/news-room/detail/02-05-2018-9-out-of-10-people-worldwide-breathe-polluted-air-but-more-countries-are-taking-action

9. Beelen R, Raaschou-Nielsen O, Stafoggia M, Andersen ZJ, Weinmayr G, Hoffmann B, et al. Effects of long-term exposure to air pollution on natural-cause mortality: an analysis of 22 European cohorts within the multicentre ESCAPE project. The Lancet. 2014 Mar 1;383(9919):785–95.

10. Pope CA, Ezzati M, Dockery DW. Fine-particulate air pollution and life expectancy in the United States. N Engl J Med. 2009 Jan 22;360(4):376–86.

11. Klepeis NE, Nelson WC, Ott WR, Robinson JP, Tsang AM, Switzer P, et al. The National Human Activity Pattern Survey (NHAPS): a resource for assessing exposure to environmental pollutants. J Expo Sci Environ Epidemiol. 2001 Jul;11(3):231–52.

12. World Health Organization, editor. Who guidelines for indoor air quality: selected pollutants. Copenhagen: WHO; 2010. 454 p.

13. Branco PTBS, Alvim-Ferraz MCM, Martins FG, Sousa SIV. Quantifying indoor air quality determinants in urban and rural nursery and primary schools. Environ Res. 2019 Sep 1;176:108534.

14. SINPHONIE. SINPHONIE – Schools Indoor Pollution and Health Observatory Network in Europe - Final Report [Internet]. EU Science Hub - European Commission. 2014 [cited 2020 Feb 18]. Available from: https://ec.europa.eu/jrc/en/publication/eur-scientific-and-technical-research-reports/sinphonie-schools-indoor-pollution-and-health-observatory-network-europe-final-report

15. Kim J, Kim S, Lee K, Yoon D, Lee J, Ju D. Indoor aldehydes concentration and emission rate of formaldehyde in libraries and private reading rooms. Atmos Environ. 2013 Jun 1;71:1–6.

16. Stranger M, Potgieter-Vermaak SS, Van Grieken R. Characterization of indoor air quality in primary schools in Antwerp, Belgium. Indoor Air. 2008 Dec 1;18(6):454–63.

17. Blondeau P, Iordache V, Poupard O, Genin D, Allard F. Relationship between outdoor and indoor air quality in eight French schools. Indoor Air. 2005;15(1):2–12.

18. Fromme H, Twardella D, Dietrich S, Heitmann D, Schierl R, Liebl B, et al. Particulate matter in the indoor air of classrooms—exploratory results from Munich and surrounding area. Atmos Environ. 2007 Feb 1;41(4):854–66.

19. Kim J, Hong T, Lee M, Jeong K. Analyzing the real-time indoor environmental quality factors considering the influence of the building occupants' behaviors and the ventilation. Build Environ. 2019 Jun 1;156:99–109.

20. Śmiełowska M, Marć M, Zabiegała B. Indoor air quality in public utility environments—a review. Environ Sci Pollut Res. 2017 Apr 1;24(12):11166–76.

21. Worobiec A, Samek L, Spolnik Z, Kontozova V, Stefaniak E, Van Grieken R. Study of the winter and summer changes of the air composition in the church of Szalowa, Poland, related to conservation. Microchim Acta. 2006 Dec 1;156(3):253–61.

22. Santamouris M, Synnefa A, Asssimakopoulos M, Livada I, Pavlou K, Papaglastra M, et al. Experimental investigation of the air flow and indoor carbon dioxide concentration in classrooms with intermittent natural ventilation. Energy Build. 2008 Jan 1;40(10):1833–43.

23. Heracleous C, Michael A. Thermal comfort conditions and air quality in educational buildings in Cyprus during the heating period: the impact of natural ventilation. In: ResearchGate [Internet]. London; 2018.

24. Majd E, McCormack M, Davis M, Curriero F, Berman J, Connolly F, et al. Indoor air quality in inner-city schools and its associations with building characteristics and environmental factors. Environ Res. 2019 Mar 1;170:83–91.

25. Wichmann J, Lind T, Nilsson MA-M, Bellander T. PM2.5, soot and NO2 indoor–outdoor relationships at homes, pre-schools and schools in Stockholm, Sweden. Atmos Environ. 2010 Nov 1;44(36):4536–44.

26. Mandin C, Trantallidi M, Cattaneo A, Canha N, Mihucz VG, Szigeti T, et al. Assessment of indoor air quality in office buildings across Europe – The OFFICAIR study. Sci Total Environ. 2017 Feb 1;579:169–78.

27. Chamseddine A, Alameddine I, Hatzopoulou M, El-Fadel M. Seasonal variation of air quality in hospitals with indoor–outdoor correlations. Build Environ. 2019 Jan 15;148:689–700.

28. Chatzidiakou L, Mumovic D, Summerfield AJ. What do we know about indoor air quality in school classrooms? A critical review of the literature. Intell Build Int. 2012 Oct 1;4(4):228–59.

29. Stranger M, Verbeke S, Täubel M, Laverge J, Wuyts D, Geyskens F, et al. Clean Air, Low Energy - Exploratory research on the quality of the indoor environment in energy-efficient buildings: the influence of outdoor environment and ventilation. 2012;346.

30. Park JS, Ikeda K. Variations of formaldehyde and VOC levels during 3 years in new and older homes. Indoor Air. 2006 Apr;16(2):129–35.

31. Pegas PN, Alves CA, Evtyugina MG, Nunes T, Cerqueira M, Franchi M, et al. Indoor air quality in elementary schools of Lisbon in spring. Environ Geochem Health. 2011 Oct 1;33(5):455–68.

32. Chao CY, Chan GY. Quantification of indoor VOCs in twenty mechanically ventilated buildings in Hong Kong. Atmos Environ. 2001 Dec 1;35(34):5895–913.

33. Chatzidiakou L, Mumovic D, Summerfield A. Is CO2 a good proxy for indoor air quality in classrooms? Part 2: Health outcomes and perceived indoor air quality in relation to classroom exposure and building characteristics. Build Serv Eng Res Technol. 2015 Mar 1;36(2):162–81.

34. Jung C-C, Wu P-C, Tseng C-H, Su H-J. Indoor air quality varies with ventilation types and working areas in hospitals. Build Environ. 2015 Feb 1;85(Supplement C):190–5.

35. Stabile L, Dell'Isola M, Russi A, Massimo A, Buonanno G. The effect of natural ventilation strategy on indoor air quality in schools. Sci Total Environ. 2017 Oct 1;595:894–902.

36. Langer S, Ramalho O, Derbez M, Ribéron J, Kirchner S, Mandin C. Indoor environmental quality in French dwellings and building characteristics. Atmos Environ. 2016 Mar 1;128:82–91.

37. Bozkurt Z, Doğan G, Arslanbaş D, Pekey B, Pekey H, Dumanoğlu Y, et al. Determination of the personal, indoor and outdoor exposure levels of inorganic gaseous pollutants in different microenvironments in an industrial city. Environ Monit Assess. 2015 Aug 27;187(9):590.

38. Zhang X, Zhao Z, Nordquist T, Norback D. The prevalence and incidence of sick building syndrome in Chinese pupils in relation to the school environment: a two-year follow-up study. Indoor Air. 2011;21(6):462–71.

39. Aizlewood C, Dimitroulopoulou C. The HOPE Project: The UK Experience: Indoor Built Environ [Internet]. 2016 Jul 27 [cited 2020 Jan 30]; Available from: https://journals.sagepub.com/doi/10.1177/1420326X06069578

40. Challoner A, Gill L. Indoor/outdoor air pollution relationships in ten commercial buildings: PM2.5 and NO2. Build Environ. 2014 Oct 1;80:159–73.

41. Huang K, Song J, Feng G, Chang Q, Jiang B, Wang J, et al. Indoor air quality analysis of residential buildings in northeast China based on field measurements and longtime monitoring. Build Environ. 2018 Oct 15;144:171–83.

42. Liu J, Dai X, Li X, Jia S, Pei J, Sun Y, et al. Indoor air quality and occupants' ventilation habits in China: Seasonal measurement and long-term monitoring. Build Environ. 2018 Sep 1;142:119–29.

43. Chatzidiakou L, Krause A, Popoola OAM, Antonio AD, Kellaway M, Han Y, et al. Characterising low-cost sensors in highly portable platforms to quantify personal exposure in diverse environments. Atmospheric Meas Tech. 2019 Aug 30;12(8):4643–57.

44. Kumar P, Morawska L, Martani C, Biskos G, Neophytou M, Di Sabatino S, et al. The rise of low-cost sensing for managing air pollution in cities. Environ Int. 2015 Feb 1;75:199–205.

45. BPIE. Europe's buildings under the microscope. A country-by-country review of the energy performance of buildings [Internet]. Brussels: Building Performance Institute Europe (BPIE); 2011 [cited 2020 Feb 18]. Available from: https://www.osti.gov/etdeweb/biblio/21514343

46. LondonAir.org. London Air Quality Network - King's College London [Internet]. [cited 2020 Apr 8]. Available from: http://www.londonair.org.uk/LondonAir/Default.aspx

47. DEFRA. Data Archive- Defra, UK [Internet]. UK Air Information Resource. Department for Environment, Food and Rural Affairs (Defra), Nobel House, 17 Smith Square, London SW1P 3JR helpline@defra.gsi.gov.uk; 2020 [cited 2020 Apr 13]. Available from: https://uk-air.defra.gov.uk/data/

48. BS EN 15251:2007. BS EN 15251:2007 Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics. 2007.

49. Eltek Dataloggers Ltd. Technical specification, TU1082 - GenII AQ110A comprehensive portable air quality monitor transmitter. [Internet]. [cited 2020 Feb 15]. Available from: https://eltekdataloggers.co.uk/pdf/user_instructions/TU1082_AQ110A_from_serial_no_32655.pdf

50. Tong Z, Chen Y, Malkawi A, Adamkiewicz G, Spengler JD. Quantifying the impact of traffic-related air pollution on the indoor air quality of a naturally ventilated building. Environ Int. 2016 Apr 1;89–90:138–46.

51. JCGM. JCGM 100:2008 - Evaluation of measurement data - Guide to the expression of uncertainty in measurement. Joint Committe for Guides in Metrology; 2008.

52. Abadie M, Wargocki P, Rode C, Rojas-Kopeinig G, Kolarik J, Laverge J, et al. Indoor Air Quality Design and Control in Low-energy Residential Buildings Annex 68 | Subtask 1: Defining the metrics. International Energy Agency - Annex 68; 2017. Report No.: AIVC Contributed Report 17.

53. JRC. The INDEX project: Critical Appraisal of the Setting and Implementation of Indoor exposure Limits in the EU. Joint Research Centre, European Commission, , Institute for Health and Consumer Protection, Physical and Chemical Exposure Unit; 2005.

54. PHE. Indoor Air Quality Guidelines for selected Volatile Organic Compounds (VOCs) in the UK. Public Health England; 2019 p. 9.

55. Dear R de, Kim J, Candido C, Deuble M. Adaptive thermal comfort in Australian school classrooms. Build Res Inf. 2015 May 4;43(3):383–98.

56. van Dronkelaar C, Dowson M, Burman E, Spataru C, Mumovic D. A Review of the Energy Performance Gap and Its Underlying Causes in Non-Domestic Buildings. Front Mech Eng

[Internet]. 2016 [cited 2020 Feb 17];1. Available from: https://www.frontiersin.org/articles/10.3389/fmech.2015.00017/full

57. HM Government. Part F - Ventilation [Internet]. 2013 [cited 2020 Feb 17]. Available from: https://www.planningportal.co.uk/info/200135/approved_documents/68/part_f_-_ventilation

58. Chen C, Zhao B. Review of relationship between indoor and outdoor particles: I/O ratio, infiltration factor and penetration factor. Atmos Environ. 2011 Jan 1;45(2):275–88.

59. Milner JT, Dimitroulopoulou C, Simon HM. Indoor concentrations in buildings from sources outdoors. ADMLC/2004/2Affiliation: Atmospheric Dispersion Modelling Liaison Committee (ADMLC) Annual Report 2004-2005; 2005 p. 82.

60. Shrubsole C, Dimitroulopoulou S, Foxall K, Gadeberg B, Doutsi A. IAQ guidelines for selected volatile organic compounds (VOCs) in the UK. Build Environ. 2019 Nov 1;165:106382.

61. Geiss O, Giannopoulos G, Tirendi S, Barrero-Moreno J, Larsen BR, Kotzias D. The AIRMEX study - VOC measurements in public buildings and schools/kindergartens in eleven European cities: Statistical analysis of the data. Atmos Environ. 2011 Jul 1;45(22):3676–84.

62. Missia DA, Demetriou E, Michael N, Tolis EI, Bartzis JG. Indoor exposure from building materials: A field study. Atmos Environ. 2010 Nov 1;44(35):4388–95.

63. Galvin J, Marashi F. CYCLOPENTANE. J Toxicol Environ Health A. 1999 Aug 15;58(1–2):57–74.

64. Camuffo D, Van Grieken R, Busse H-J, Sturaro G, Valentino A, Bernardi A, et al. Environmental monitoring in four European museums. Atmos Environ. 2001 Jan 1;35:S127–40.

65. Steinemann A, Wargocki P, Rismanchi B. Ten questions concerning green buildings and indoor air quality. Build Environ. 2017 Feb 1;112:351–8.

66. Mead MI, Popoola OAM, Stewart GB, Landshoff P, Calleja M, Hayes M, et al. The use of electrochemical sensors for monitoring urban air quality in low-cost, high-density networks. Atmos Environ. 2013 May 1;70:186–203.

67. EPA. Ambient Air Quality Surveillance (Subchapter C). Environmental Protection Agency; 2016. Report No.: 40 CFR Parts 58.

68. Karagulian F, Gerboles M, Barbiere M, Kotsev A, Lagler F, Borowiak A, et al. Review of sensors for air quality monitoring. [Internet]. 2019 [cited 2020 Jan 30]. Available from: http://publications.europa.eu/publication/manifestation_identifier/PUB_KJNA29826ENN

69. Jiang R-T, Acevedo-Bolton V, Cheng K-C, Klepeis NE, Ott WR, Hildemann LM. Determination of response of real-time SidePak AM510 monitor to secondhand smoke, other common indoor aerosols, and outdoor aerosol. J Environ Monit JEM. 2011 Jun;13(6):1695–702.

70. Wang Z, Calderón L, Patton AP, Allacci MS, Senick J, Wener R, et al. Comparison of real-time instruments and gravimetric method when measuring particulate matter in a residential building. J Air Waste Manag Assoc. 2016 Nov 1;66(11):1109–20.

Long-term, continuous air quality monitoring in a cross-sectional study of three UK non-domestic buildings

Samuel Stamp[a], Esfand Burman[a], Clive Shrubsole[a], Lia Chatzidiakou[b], Dejan Mumovic[a], Mike Davies[a]

[a] Institute for Environmental Design and Engineering, University College London (UCL), Central House, 14 Upper Woburn Place, London, WC1H 0NN, UK
[b] Department of Chemistry, University of Cambridge, Cambridge, CB2 1EW, UK

Corresponding author: samuel.stamp@ucl.ac.uk

Highlights

- **Long-term continuous and seasonal IAQ measurements in hospital, school and office.**
- **Mechanically ventilated buildings demonstrated effective particulate filtration.**
- **Absence of nitrogen dioxide filtration led to high indoor-outdoor ratios.**
- **Significant variation in indoor-outdoor ratios caused by increased ventilation.**
- **Measurements of benzene and several formaldehyde measurements exceeded guidelines.**

Declaration of interests

☒ 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.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: