Indoor Air Quality in School Classrooms

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CIBSE School Design Group

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My hats

- **Lecturer in Indoor Air - Leeds**: Research and te and physical dimensions quality (IAQ)
- **Co-Founder & CEO - N** IAQ monitoring technolo services
- **Regional Clean Air Cha** across engineering, atm and social science to de fair solutions for air quali

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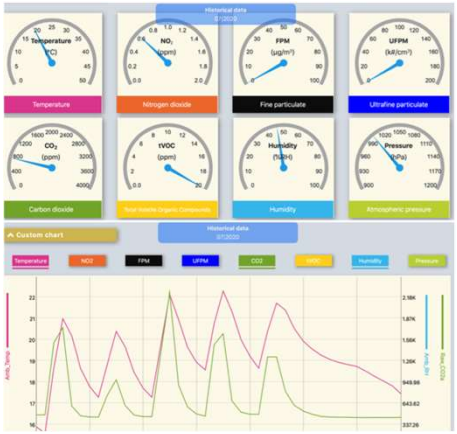
NAQTS: Who we are and what we do

- National Air Quality Testing Services (NAQTS) was founded in 2015 with the mission to provide holistic indoor air quality information to inform choices and improve quality of life.

- We seek to improve awareness of indoor air quality through widespread public and commercial monitoring using our holistic, high-quality, air pollution monitoring technology.

Equipment

Testing Services



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SAMHE

TAPAS

Tackling air pollution at school

CALM

Clean Air Living Matters
Exploring Reading

Clean Air Programme

SAQN

STFC
AIR QUALITY
NETWORK

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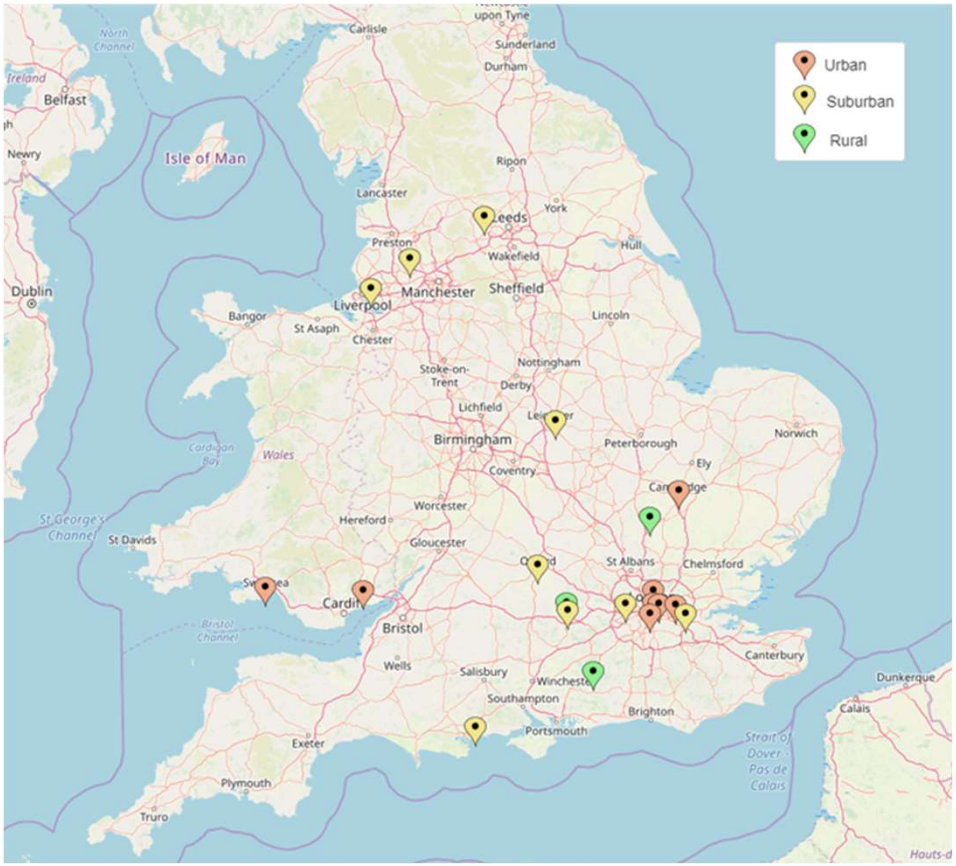
Overview

- This presentation includes indoor air quality data from 20 primary school classrooms across England and Wales during two school terms (Jan-Apr 2020, Oct 2020)

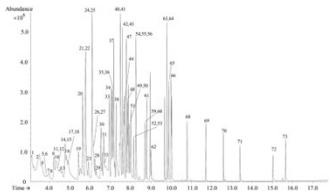
- Measurements were made in a mix of urban, suburban, and rural testing locations



IAQ measurements

- All air quality measurements were facilitated by the NAQTS V2000
- A wide range of regulated and non-regulated air pollutants were measured for a holistic understanding of indoor air quality
- Continuous monitoring measurements were taken at 1 min intervals, and were supported by discrete air sampling

NAQTS V2000 for continuous and discrete air sampling



… with a focus on
VOCs
NO_2

	Main sources	Recommended max level	Impact on health
$PM_{2.5}$	Fuel combustion (traffic, heating, power generation)	Annual mean (WHO) 10 µg/m³ 24h mean (WHO) 25 µg/m³	Asthma, Cardiovascular diseases
Ultrafine particles		10,000 #/cm³	Under evaluated
NO_2		Annual mean (WHO) 40 µg/m³ Hourly mean (WHO) 200 µg/m³	Asthma, lower immunity to respiratory diseases
VOCs	Paint, furniture, flooring, cleaning products, cosmetics, aerosols, traffic, agriculture	8h mean (UK Gov Building Regulation) 300 µg/m³	Eye, nose and throat irritation, shortness of breath, headaches, fatigue, nausea, dizziness and skin problems
CO_2	Respiration	Occupied period daily mean (DfE) 1000-1500 ppm	Drowsiness, headache, loss of attention, ...

V2000 remote control & monitoring

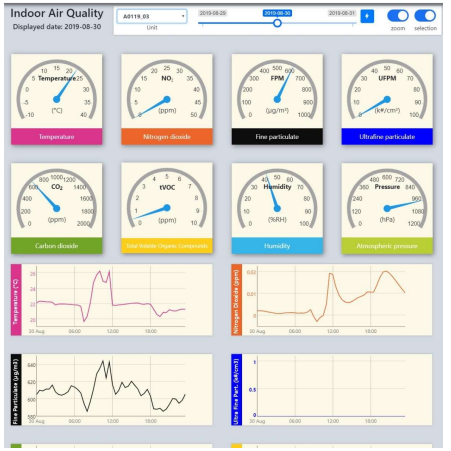
- All air quality data was automatically beamed to the NAQTS Cloud
- A bespoke webpage was developed for the schools so that the pupils and teachers could view the air quality data in near real-time

V2000

GSM

Server

Schools



Real time monitoring and data processing

Support STEM activities

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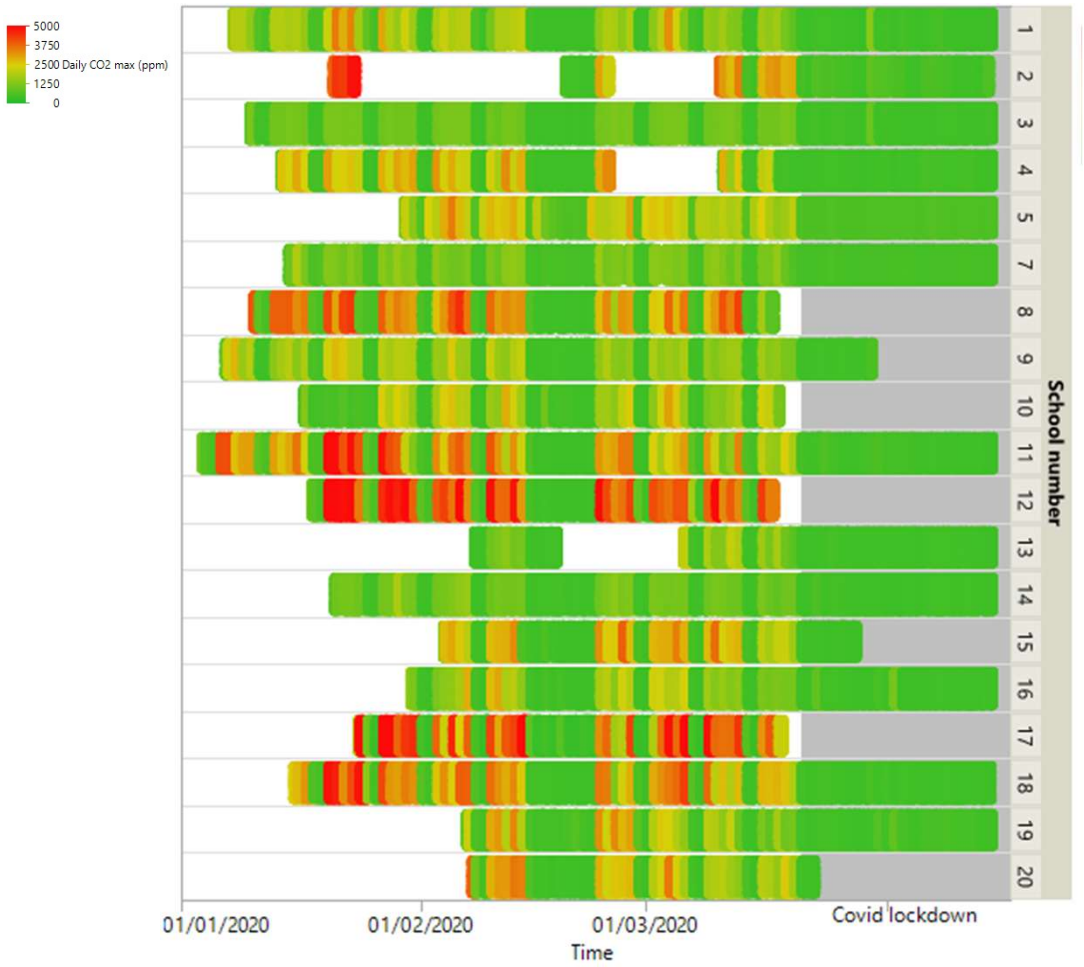
Pre and post COVID measures

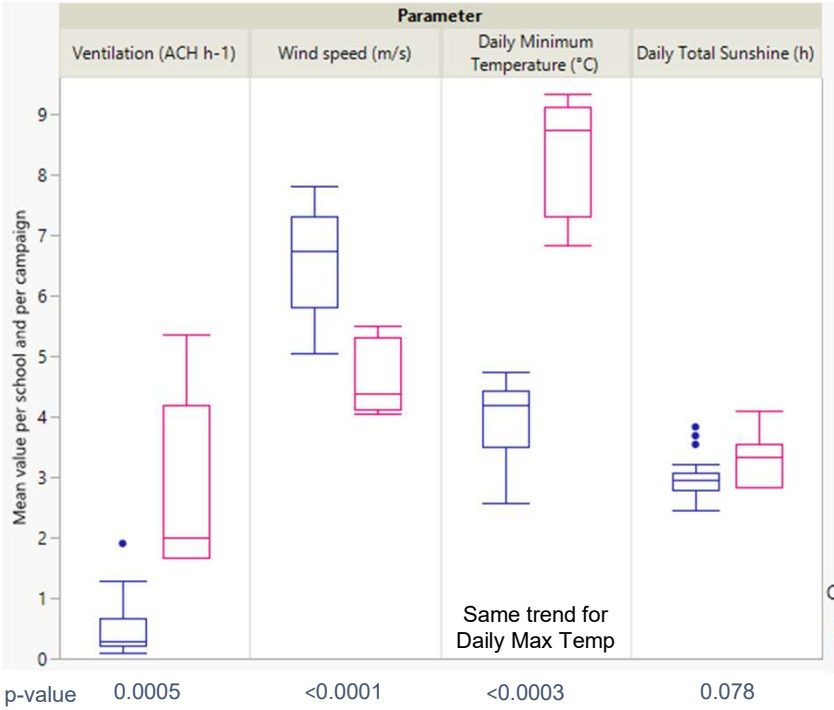
- Project was stopped earlier than planned
- Fewer air quality measurements
- Less thermal desorption sampling performed
- Mitigated by an additional autumn sampling campaign

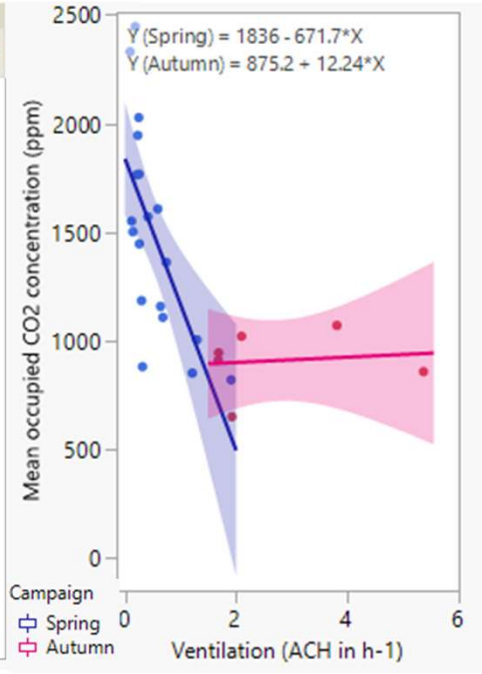
Daily maximum CO_2 concentration (ppm) as a tracer of classroom occupancy



Differences between Spring & Autumn campaigns

- Same schools monitored with the same experimental plan
- Very different conditions due to COVID-19 measures and the different season
- Focus on trends confirmation vs new insights





p-values calculated from the mean values per school and per campaign, using the t-test method or the nonparametric comparisons for each pair using Wilcoxon method depending on the data normality (95% confidence)

CO_2 Results

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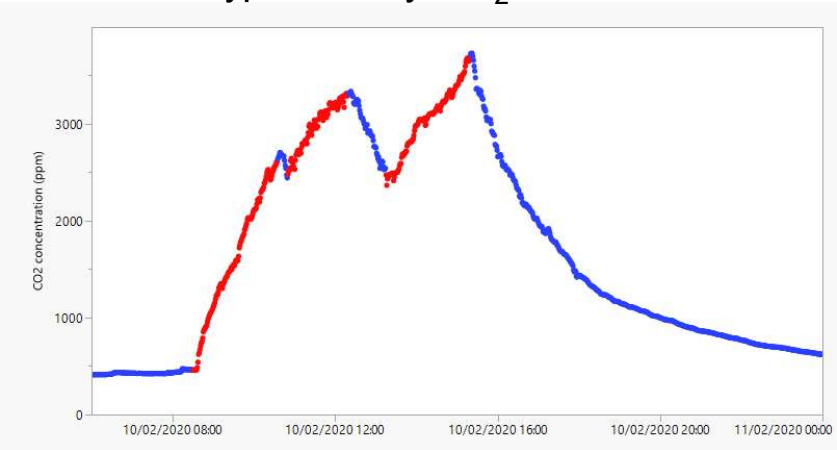
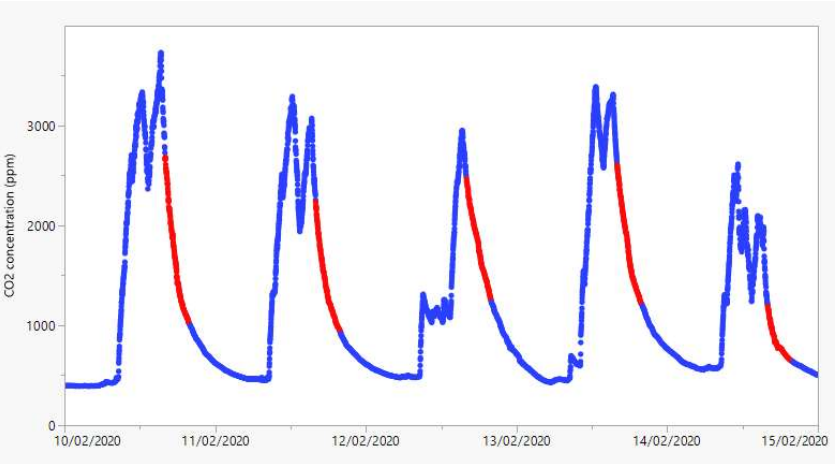
Why look at CO_2?

- Primarily from exhaled breath
- CO_2 is not toxic at concentrations usually found in classrooms. However, higher concentrations can lead to detrimental impacts
- Higher concentrations are a function of room occupancy and the room ventilation rate (Air Changes per Hour - ACH)
- CO_2 is a good probe to assess the room ventilation rate

Typical Daily CO_2 Profile



Weekly CO_2 Profile



CO_2 concentration	Impacts
Up to 1,000ppm	Concentrations typical of occupied indoor spaces with good air change
1,000-2,000ppm	Complaints of drowsiness and poor air.
2,000-5,000 ppm	Headaches, sleepiness and stagnant, stale, stuffy air. Poor concentration, loss of attention, increased heart rate and slight nausea may also be present.
5,000	Workplace exposure limit (as 8-hour TWA).
>40,000 ppm	Exposure may lead to serious oxygen deprivation resulting in permanent brain damage, coma, even death.

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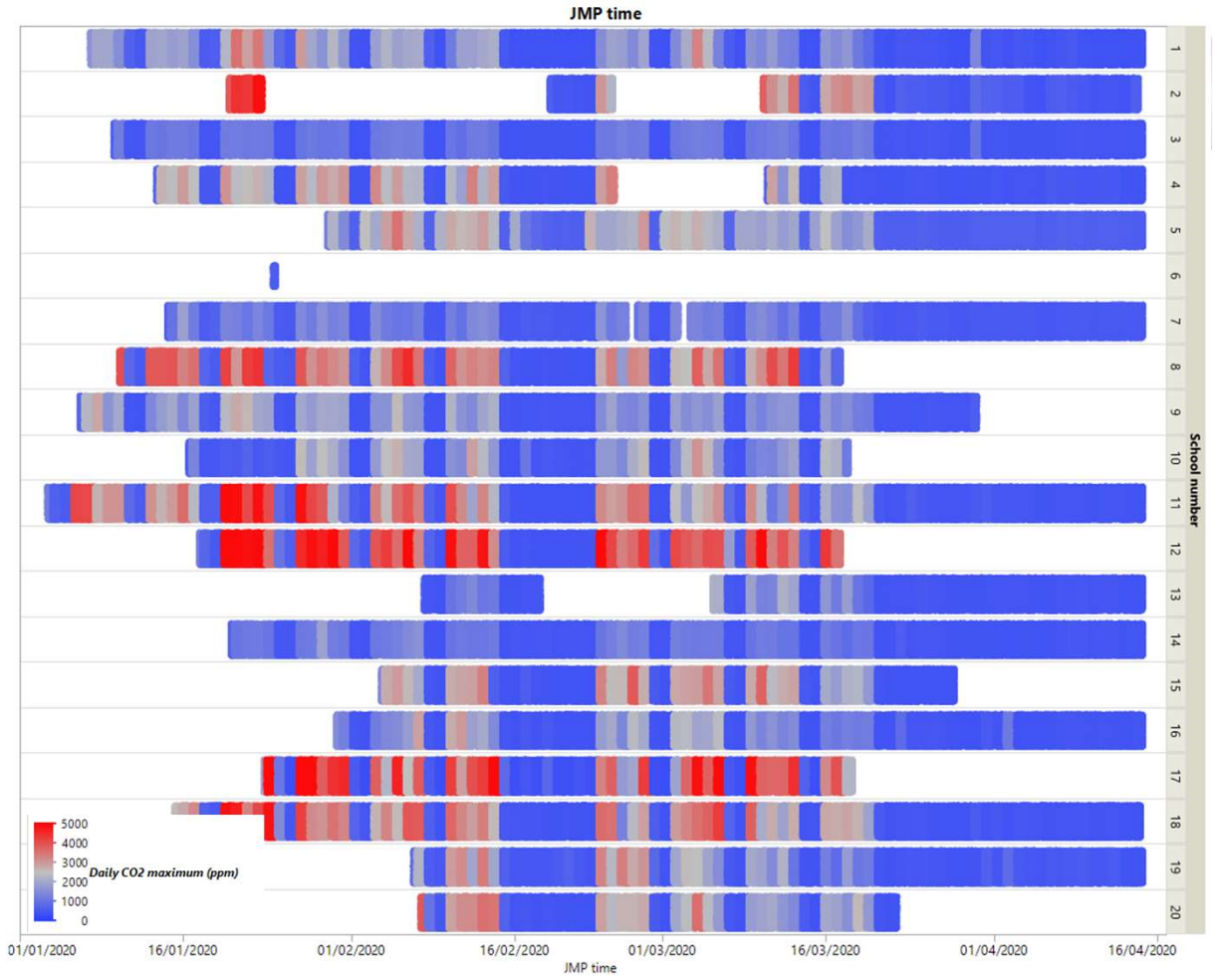
Overview of Classroom CO_2

- Measurements were made under normal ‘real-world’ classroom use with no control or visibility on opened windows /doors
- Strong impact of presence of children
- Half term and week ends clearly visible
- Strong impact of the school closure
- High variability on maximum concentrations between schools



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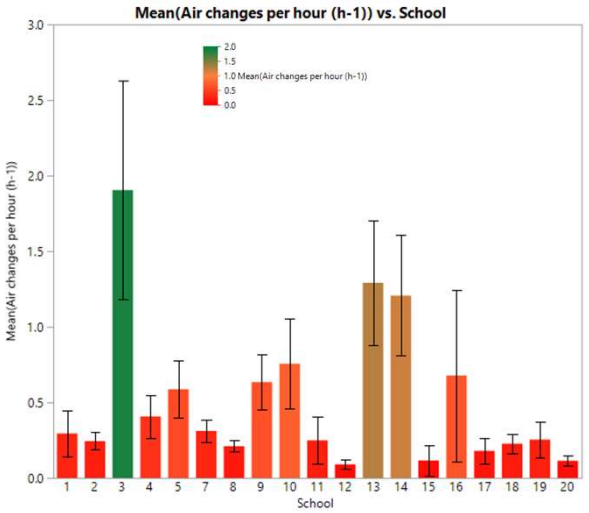
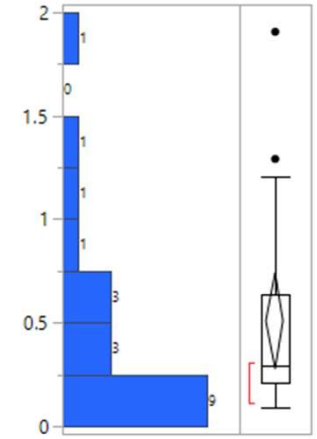
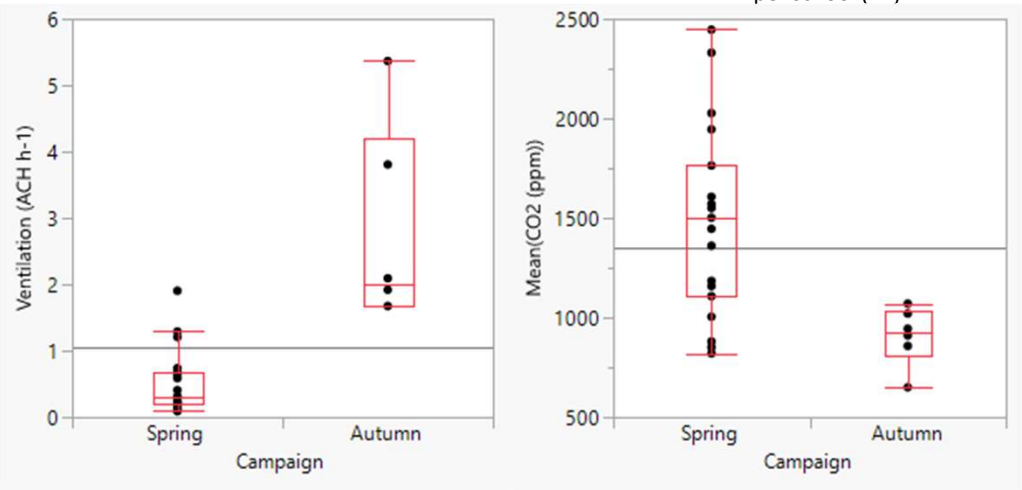
Air change rates

- In the Spring measurement campaign most classrooms had a very low ACH, below 0.5 h^{-1}
- In the Autumn measurement campaign Schools did increase the ventilation in classrooms, and this decreased the mean occupied CO_2 concentration



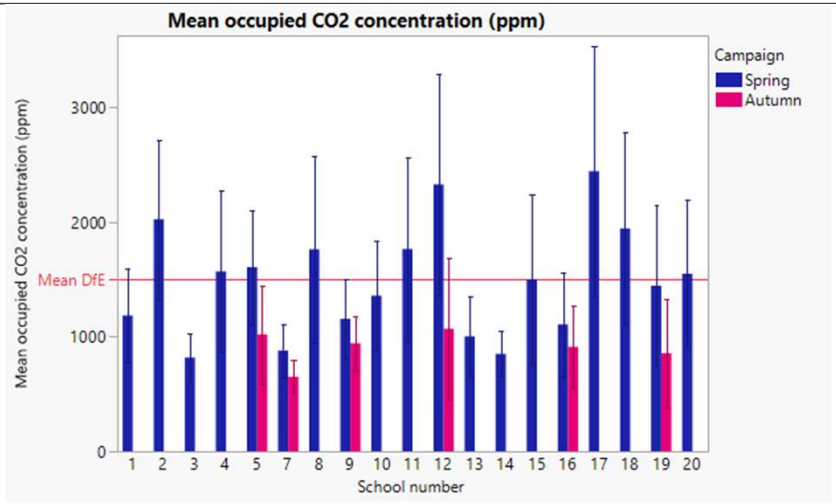


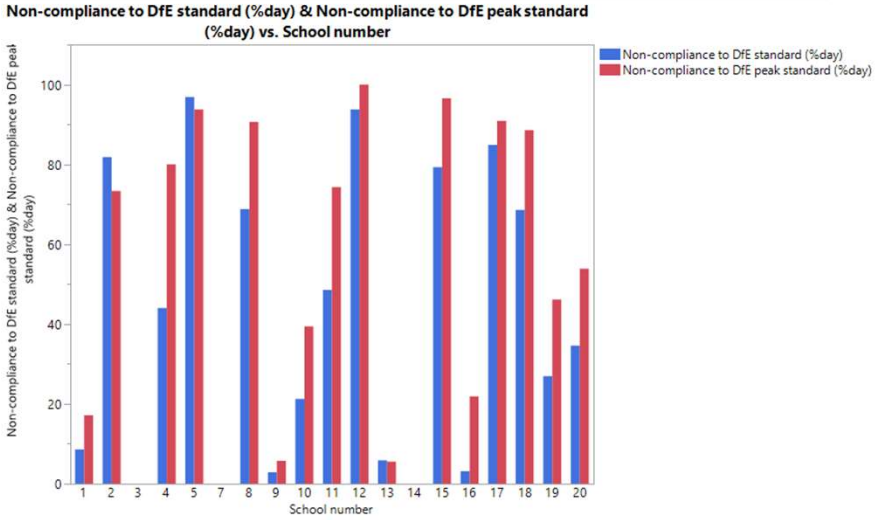
Histogram of mean ACH per school (h^{-1})



Department for Education Guidelines – BB101

- Many schools regularly exceed the DfE CO_2 concentration recommendations [1]
- Much better situation during the Autumn extension



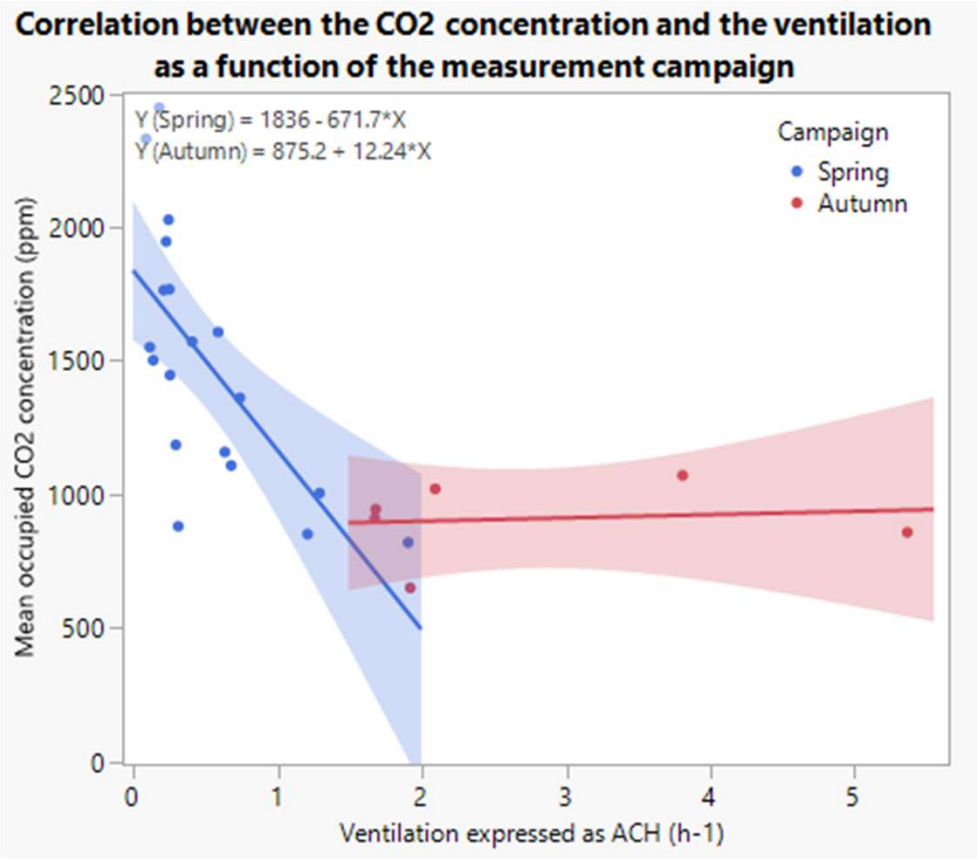


[1] Guidelines on ventilation, thermal comfort and indoor air quality in schools Building Bulletin 101

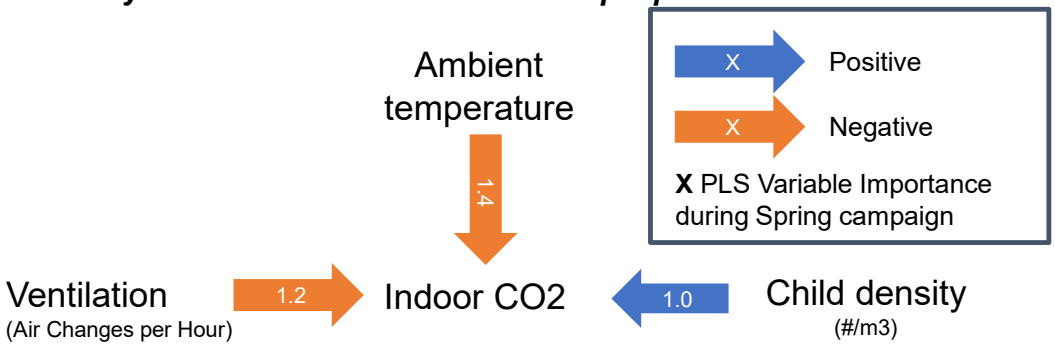
	Department for Education [1]	
	Daily average concentration during the occupied period	Maximum concentration for more than 20 consecutive minutes each day
Natural ventilation	1500 ppm	2000 ppm
Mechanical ventilation	1000 ppm	1500 ppm

Key parameters influencing CO_2

- Spring – ventilation, temperature, and room occupancy key factors
- Autumn - ventilation and temperature are not correlated to CO_2 anymore. Child density is more significant



Principal Least Square analysis +
Analysis of correlation between multiple pair of variables



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How to relate CO_2 concentrations to health concerns?

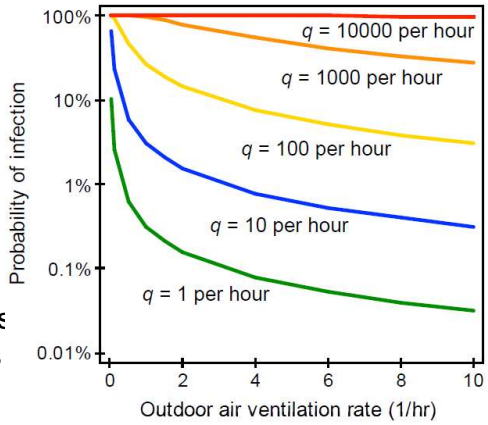
- Beyond its recognised impact on wellbeing and attention…
- CO_2 is a good probe to assess the infection risk for airborne diseases
- CO_2 can be used to calculate both:
  - the probability of infection for given diseases [1,2]
  - the indoor air rebreathed fraction [3]

$$N_C = S\left(1 - e^{-\frac{Iqp}{Q}t}\right)$$

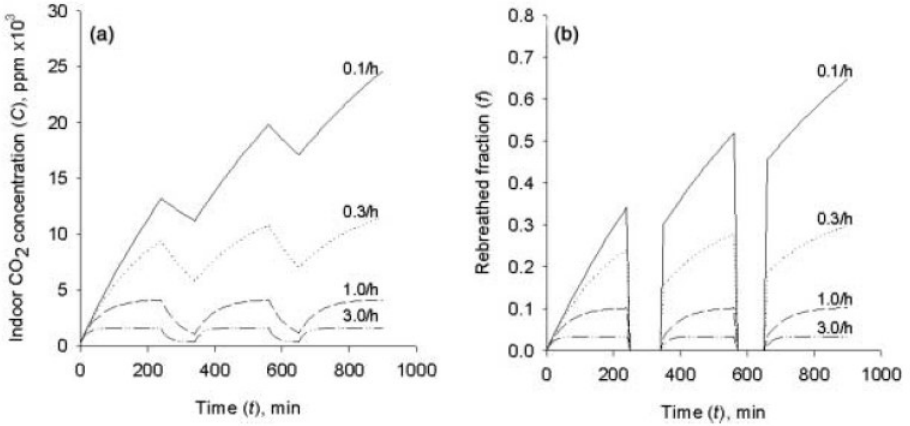
Wells-Riley equation [1, 2]

with

N_C	number of new cases infected
S	number of susceptible people in the room
I	number of infective people in the room
p	pulmonary ventilation rate of susceptible individuals
q	"quantum" describing how infectious the disease is
Q	room ventilation rate



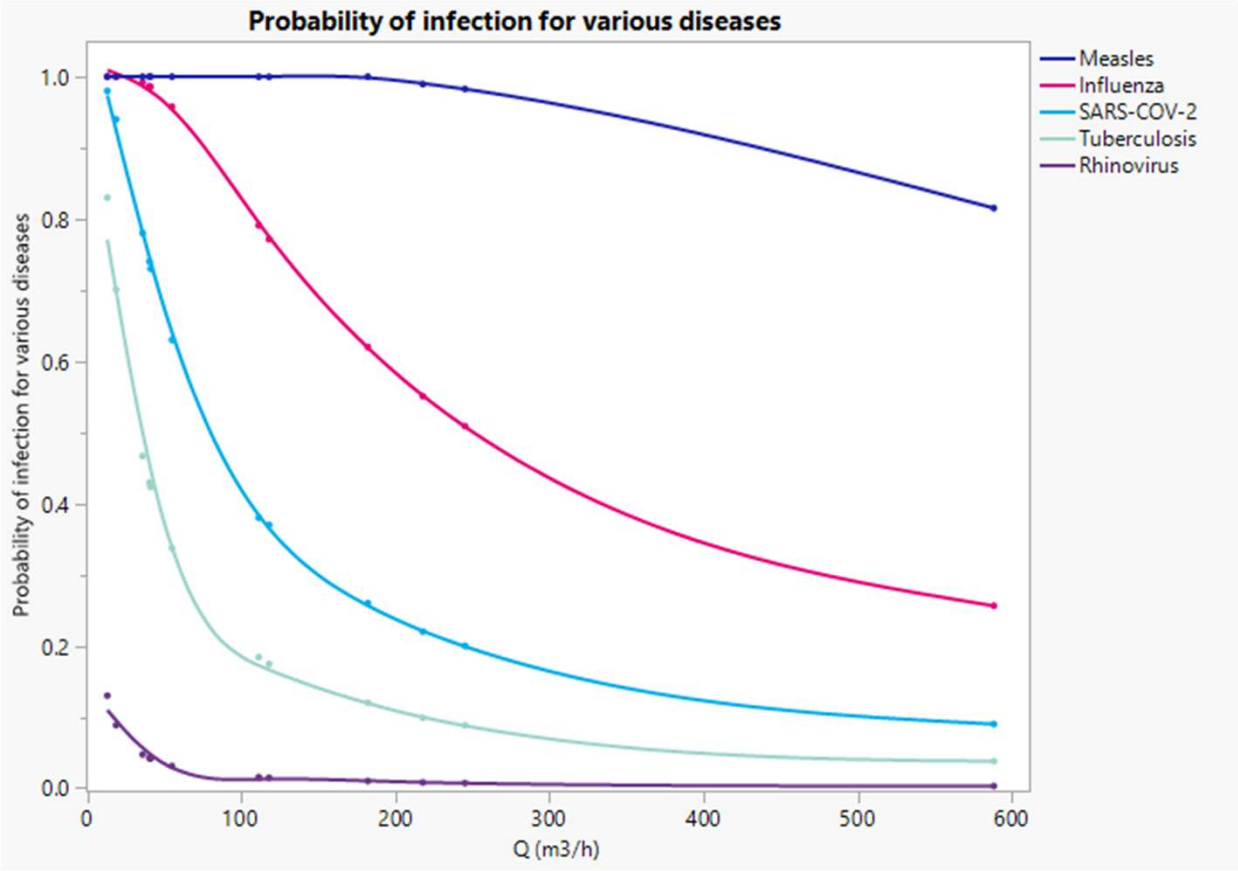
From [3]



[1] Wells, W. F. 1955 Airborne contagion and air hygiene. Cambridge, MA: Harvard University Press
[2] Riley, E. C., Murphy, G. & Riley, R. L. 1978 Airborne spread of measles in a suburban elementary school. Am. J. Epidemiol. 107, 421 –432
[3] Stephens B. 2012 NAFA Foundation Report, HVAC filtration and the Wells-Riley approach to assessing risks of infectious airborne diseases

Impact of ventilation on infection risk

- Probability for a student in presence of one infected person in the classroom for 5.5h to get infected as a function of the Air Change per Hour
- *Quantum values from [1] for SARS-COV-2 and [2] for the other diseases*
- For SARS-CoV-2, increasing the ACH significantly reduces the infection risk. However, there are diminishing returns…

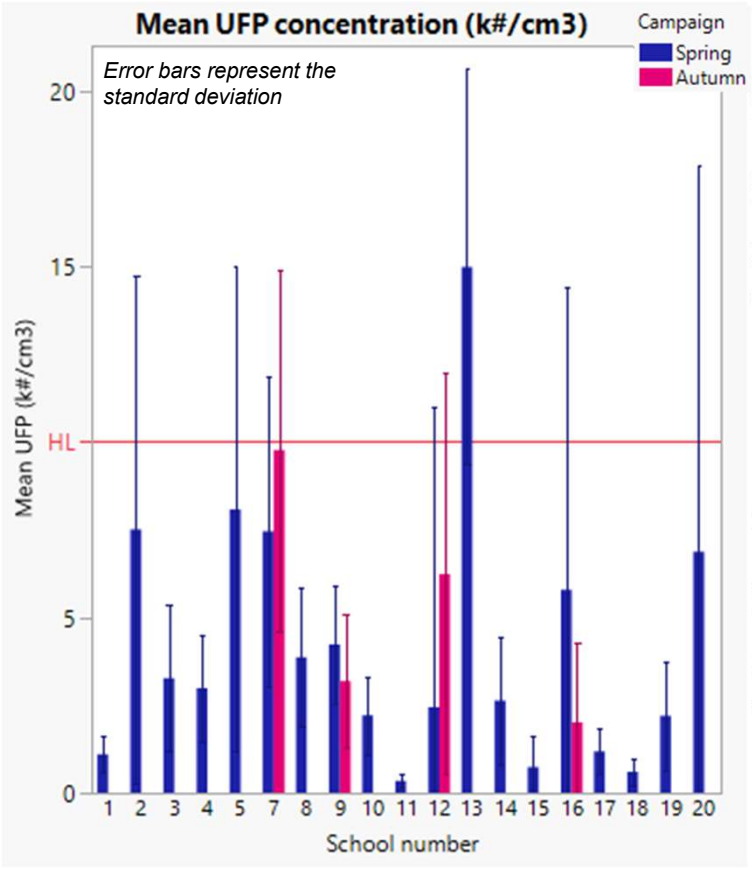


[1] Buonanno G., *Environment International* 141 (2020) 105794
[2] Stephens B. 2012 NAFA Foundation Report, HVAC filtration and the Wells-Riley approach to assessing risks of infectious airborne diseases

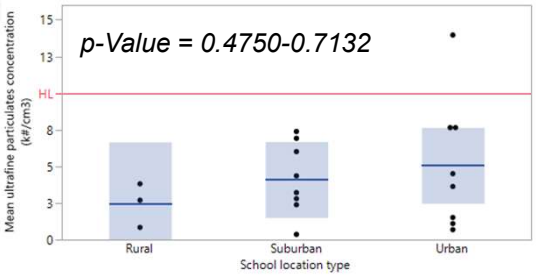
PM Results

Ultrafine particles

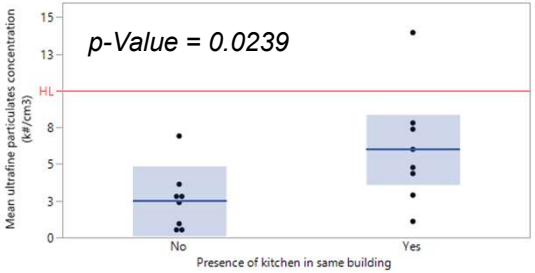
- A very diverse picture both between schools and over time
- What is an acceptable concentration?
- No correlation found with $PM_{2.5}$ concentrations
- No significant impact of the school location type
- Strong impact of the presence of a kitchen
- Main sources of ultrafine particles were likely internal to the school



Location



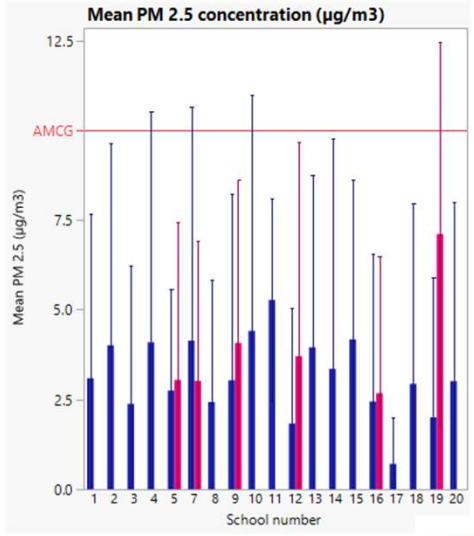
Presence of Kitchen



Nonparametric comparison for each pair using the Wilcoxon method

$PM_{2.5}$

- A very diverse picture both between schools and over time
- Strong impact of weather on outdoor PM concentrations
- Indoor $PM_{2.5}$ concentration was mainly dictated by the outdoor air pollution



Principal Least Square analysis +
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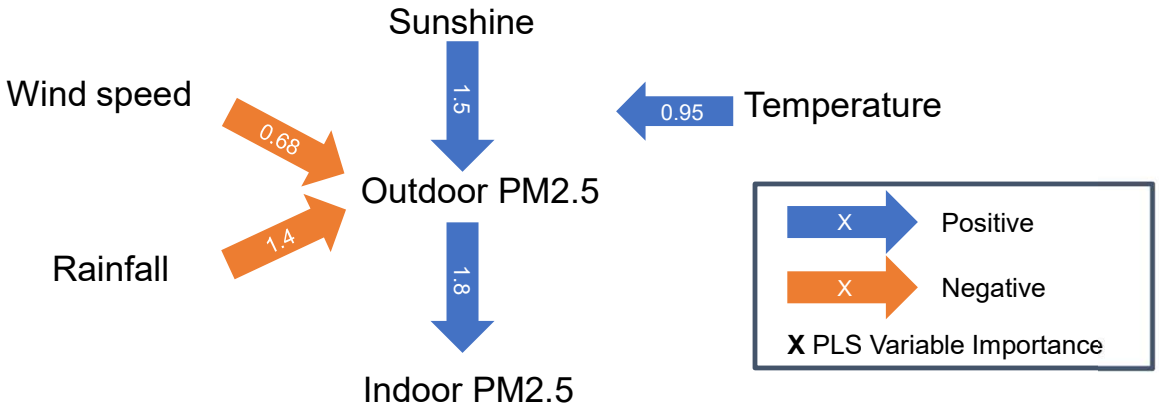
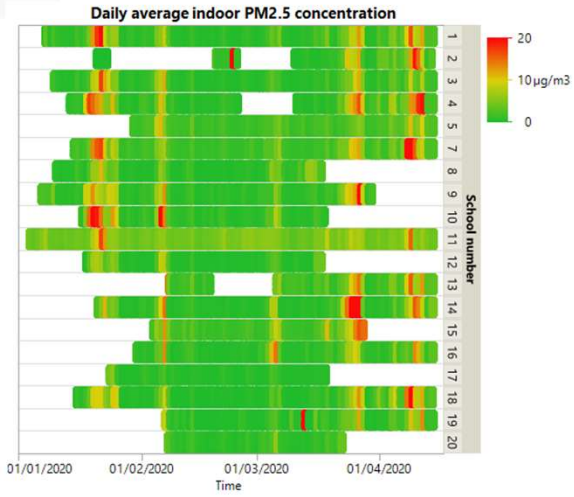
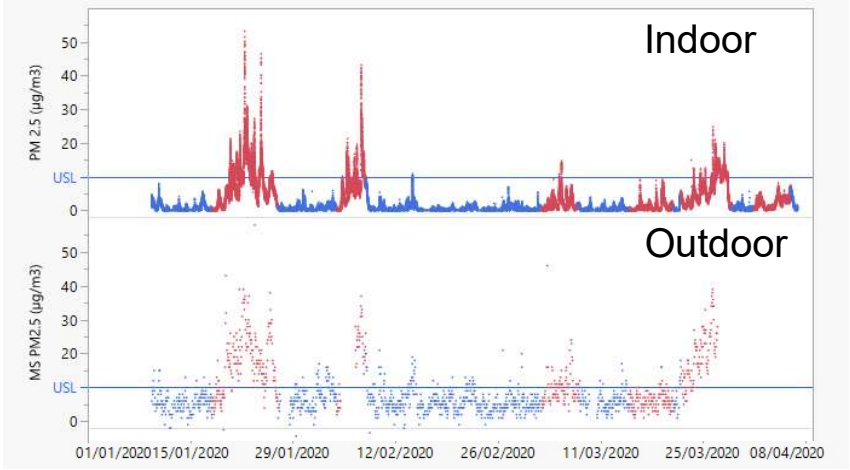




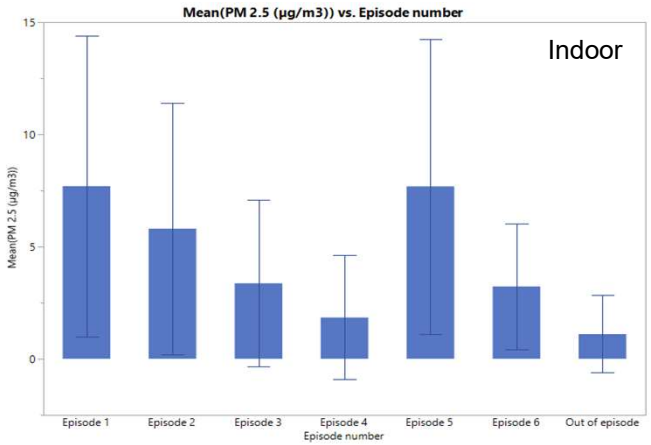
Key Parameters Influencing $PM_{2.5}$ – Outdoor Air Quality

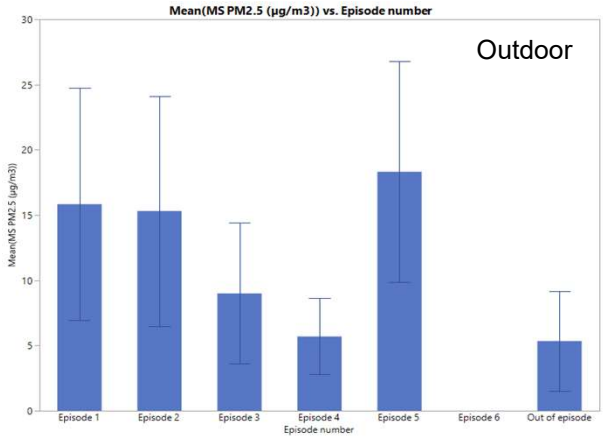
- Nationwide episodes of high outdoor PM2.5 identified
- High Outdoor PM2.5 episodes simultaneously affect all schools nationwide
- Indoor peaks match with outdoor peaks well



Example School

- V2000 PM2.5 data compared to outdoor PM2.5 data from the nearest monitoring station
- Highlighted in red are points that fall within a high PM episode
- The Upper Spec Limit (USL) is the WHO annual mean recommended level for illustration





Average outdoor PM2.5 all schools combined for each episode, and for the time in between episodes. The error bars show the standard deviation.

NO_2 Results

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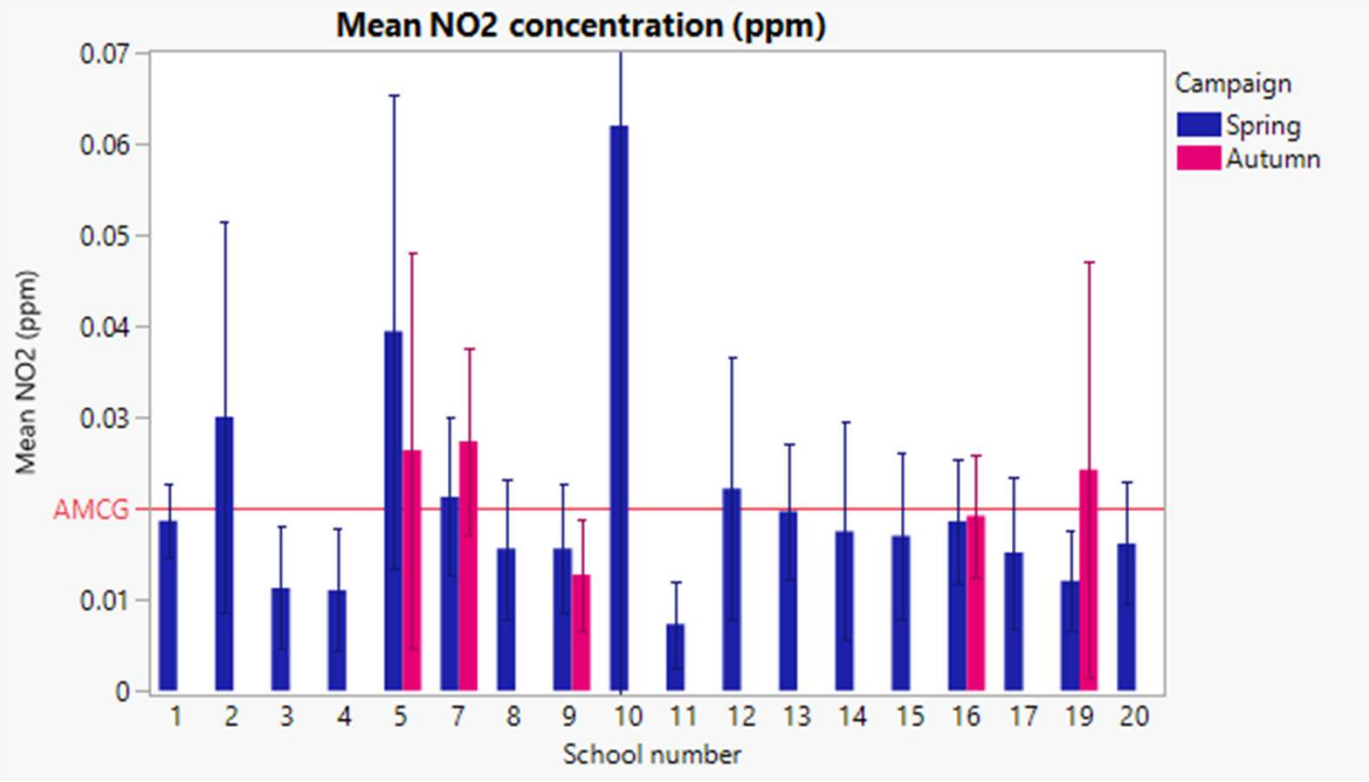
Overview of classroom NO_2

- NO_2 low-cost sensor absolute numbers should be treated with caution, but are good for identifying trends
- The indoor NO_2 concentrations in some schools is higher than ideal



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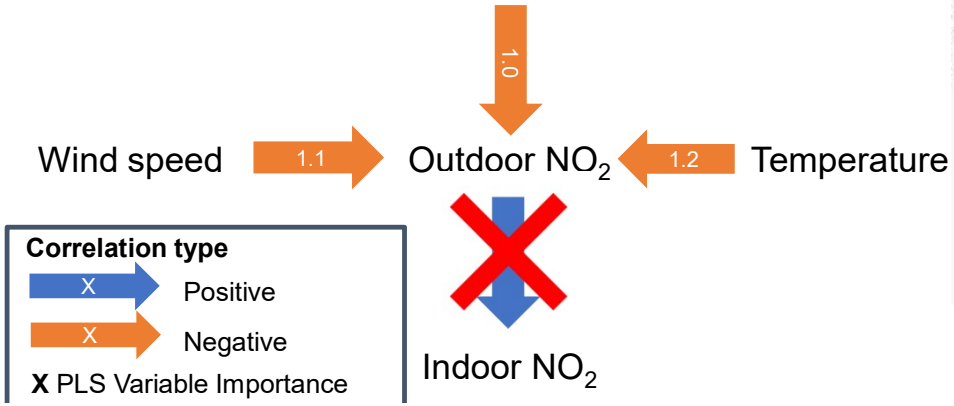
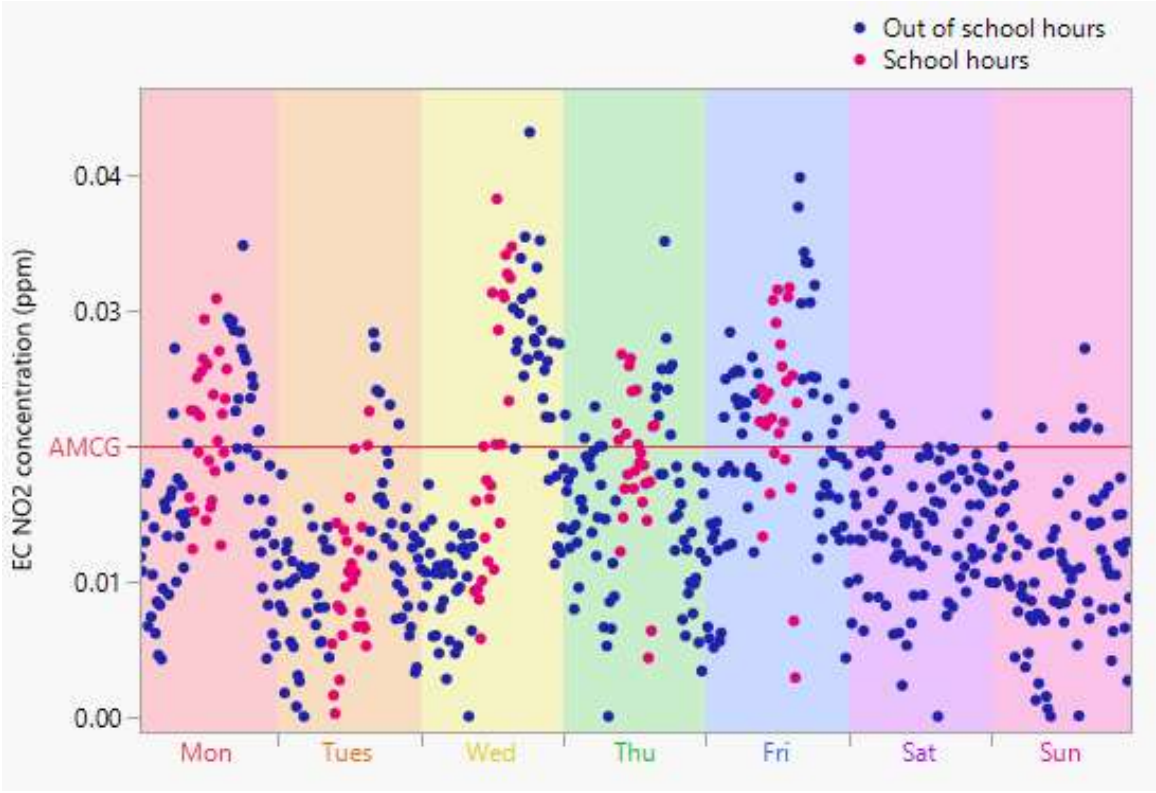
Key Parameters Influencing NO_2 concentrations

- There is a daily NO_2 concentration cycle
- Strong impact of weather on outdoor NO_2 concentrations

Principal Least Square analysis +
Analysis of correlation between multiple pair of variables





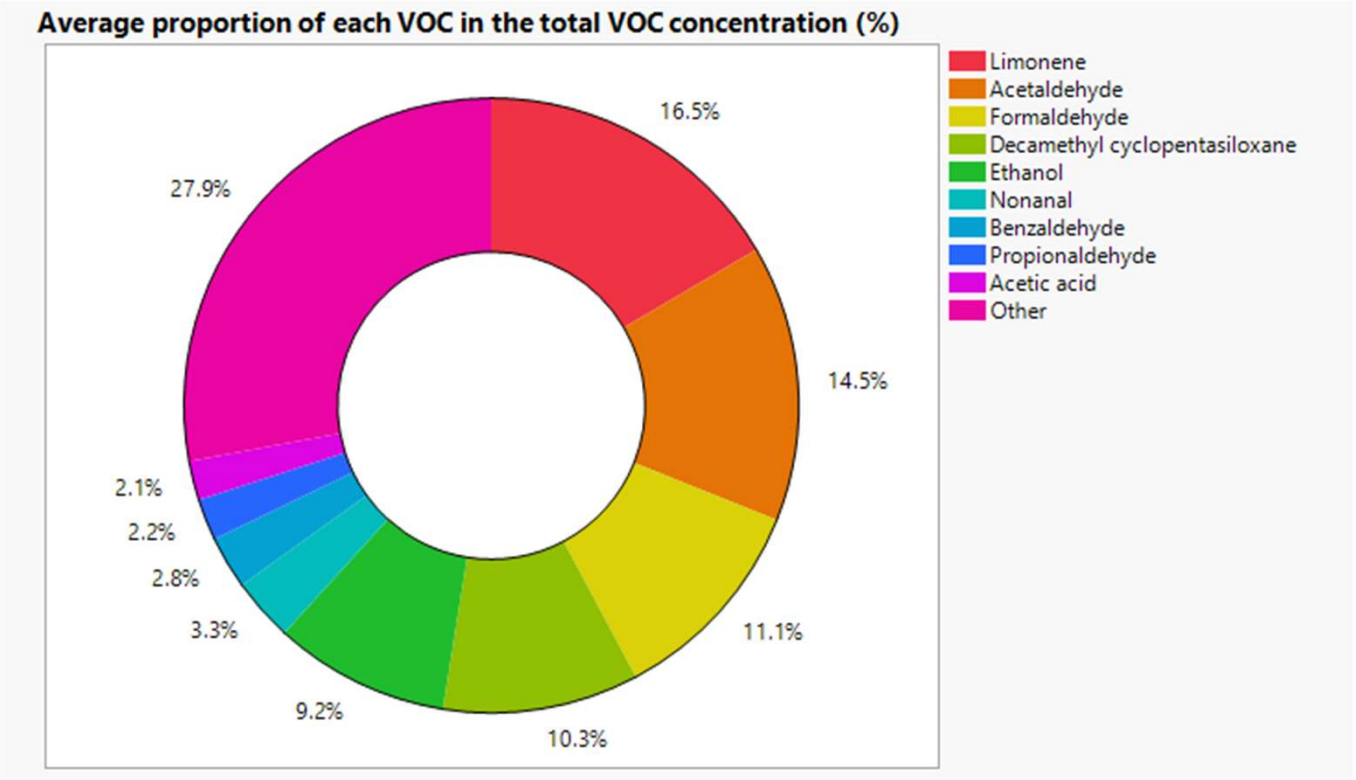
VOCs Results

VOCs results

- A wide range of VOCs from differing sources were prevalent
- VOCs dominated by 5 species

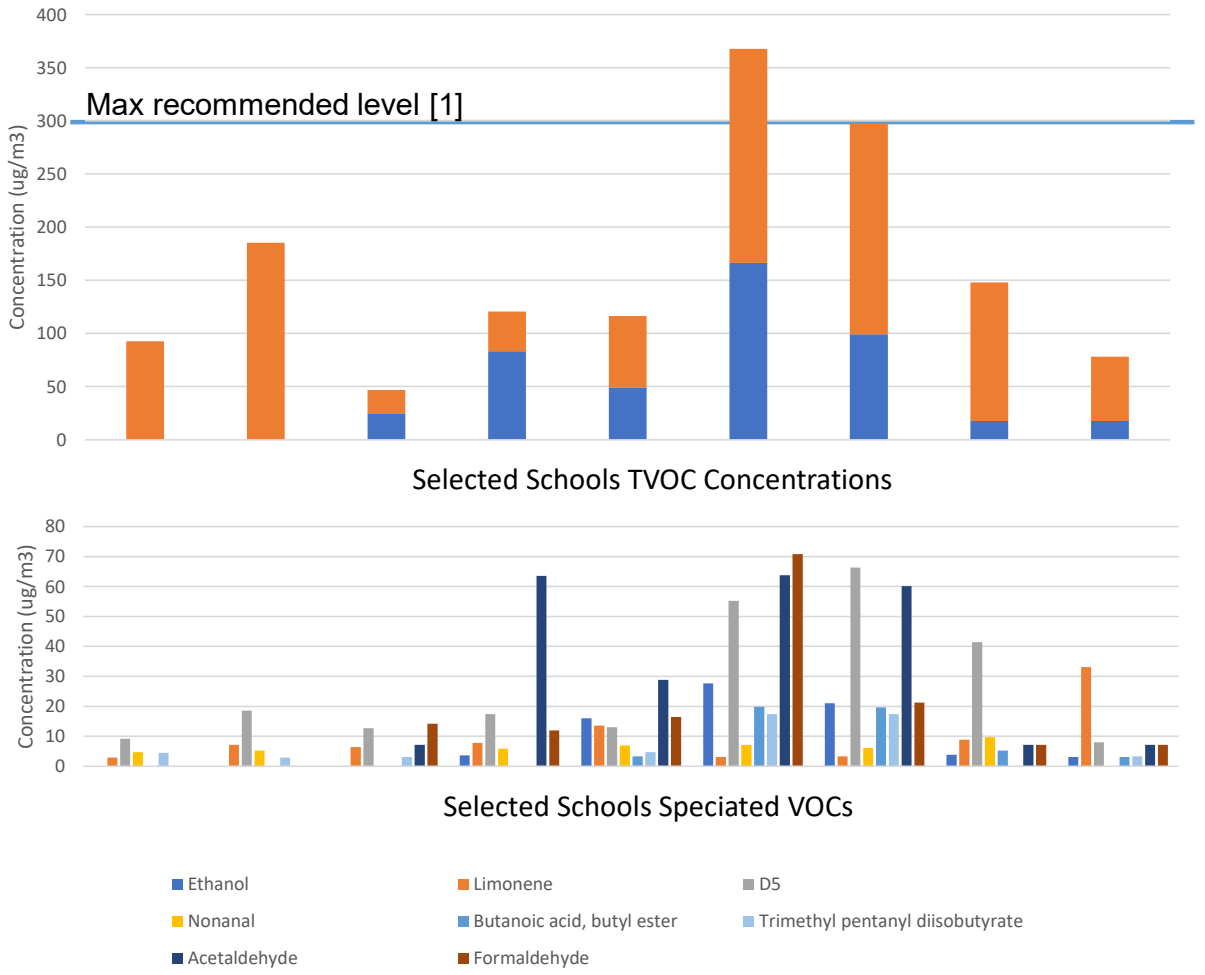
Top 5 of the 80 VOCs identified

VOC	Source
Limonene	Cleaning products, food flavouring
Acetaldehyde	Furniture, cleaning products, cosmetics, etc.
Formaldehyde	Furniture, cleaning products, cosmetics, etc.
D5	Cosmetics
Ethanol	Disinfectants, cleaning solutions



Overview of classroom VOCs

- TVOC below recommended level [1] in all but one measured classroom
- Some higher TVOC concentrations can be explained by recent refurbishment
- Formaldehyde and acetaldehyde remain below recommended levels (100 and 160 respectively for annual mean)



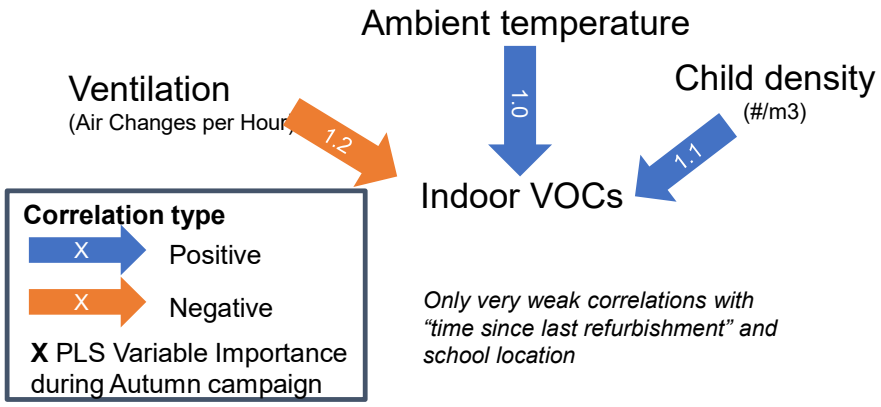
[1] UK Government Building Regulations Part F.

Key parameters influencing VOCs

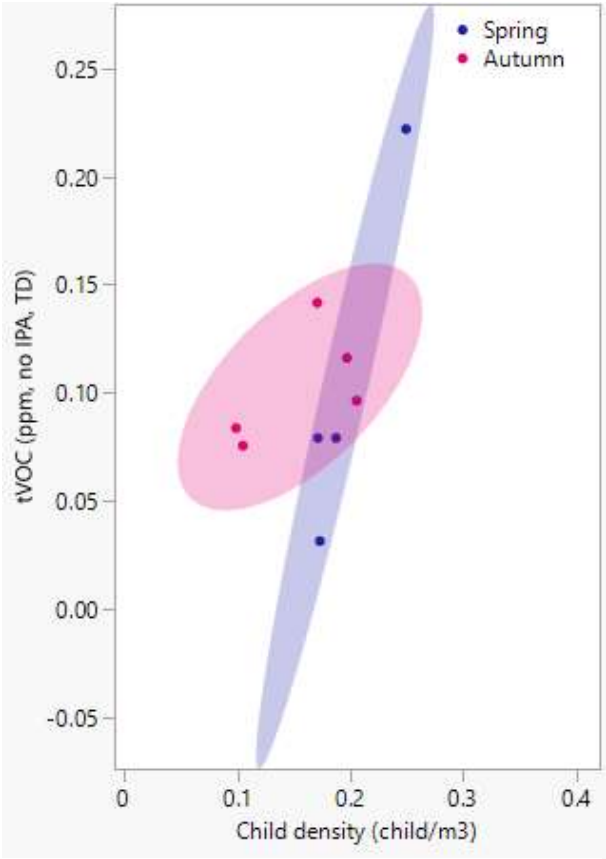
- Room occupancy, temperature and ventilation are the key parameters influencing the tVOC concentration

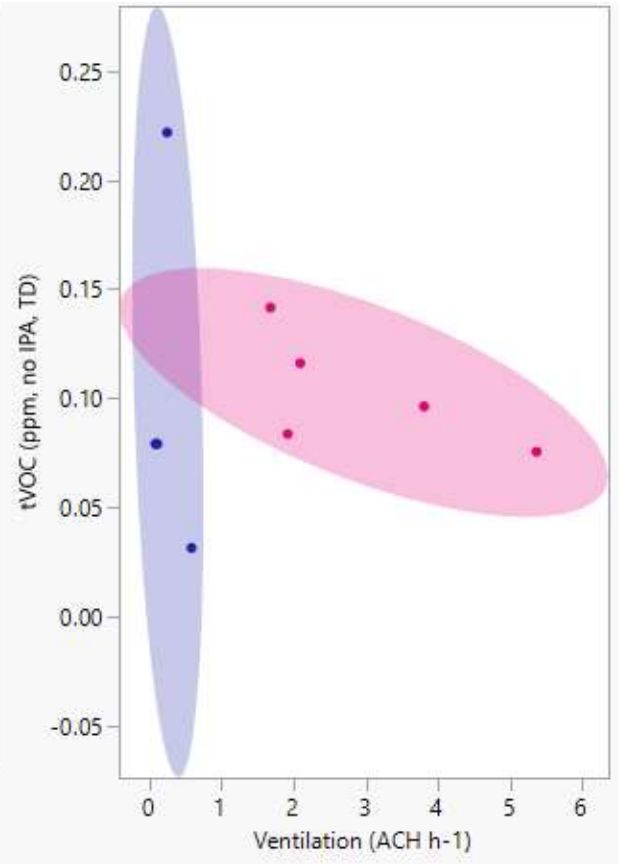
- All the parameters are more significant during the Spring campaign when the ventilation rate was lower

Principal Least Square analysis + Analysis of correlation between multiple pair of variables



Only very weak correlations with "time since last refurbishment" and school location





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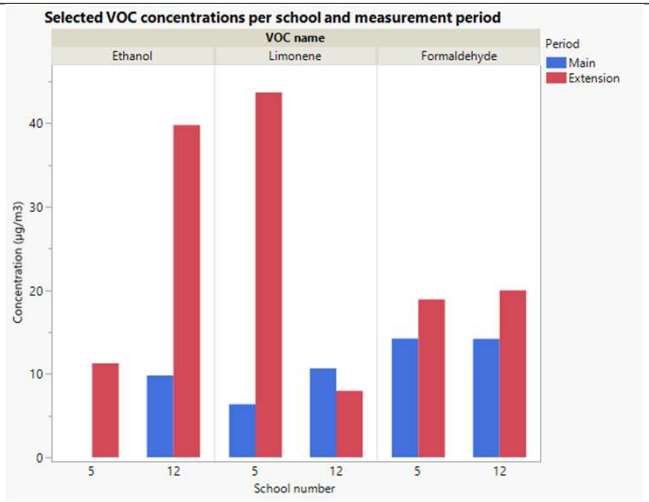
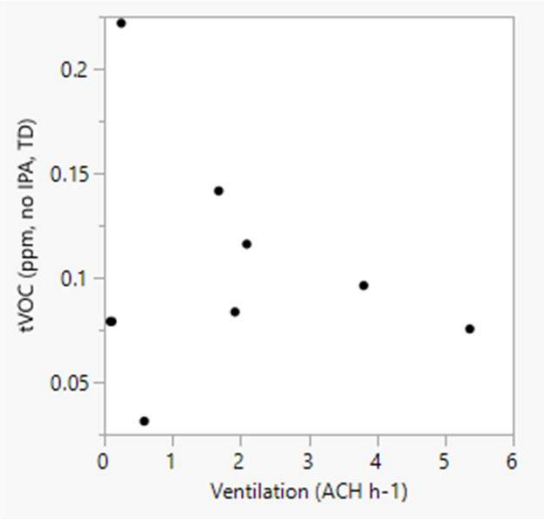
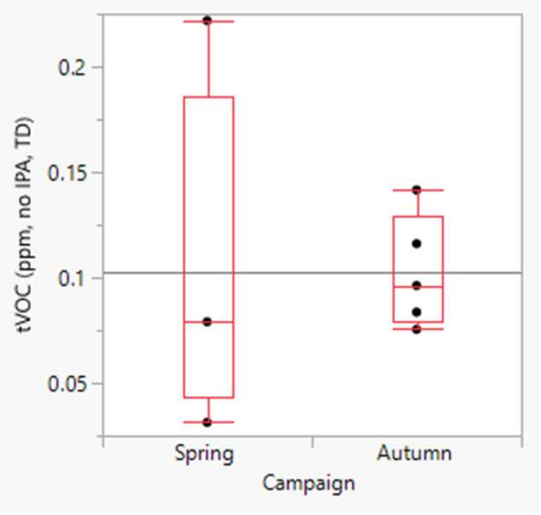
Increase of select VOCs due to COVID measures

- Despite increased ventilation being a key parameter influencing the TVOC concentration, TVOCs did not significantly decrease due to an increased use of disinfectant and hand sanitiser







Healthy and Sustainable Schools

IAQ – Energy dilemma

- 67k buildings across >21k schools
- Schools are 15% of carbon emissions from public buildings in the UK
- More energy efficient schools require higher levels of air tightness to prevent heat loss
- Unintended consequences: worse IAQ / overheating / virus transmission?

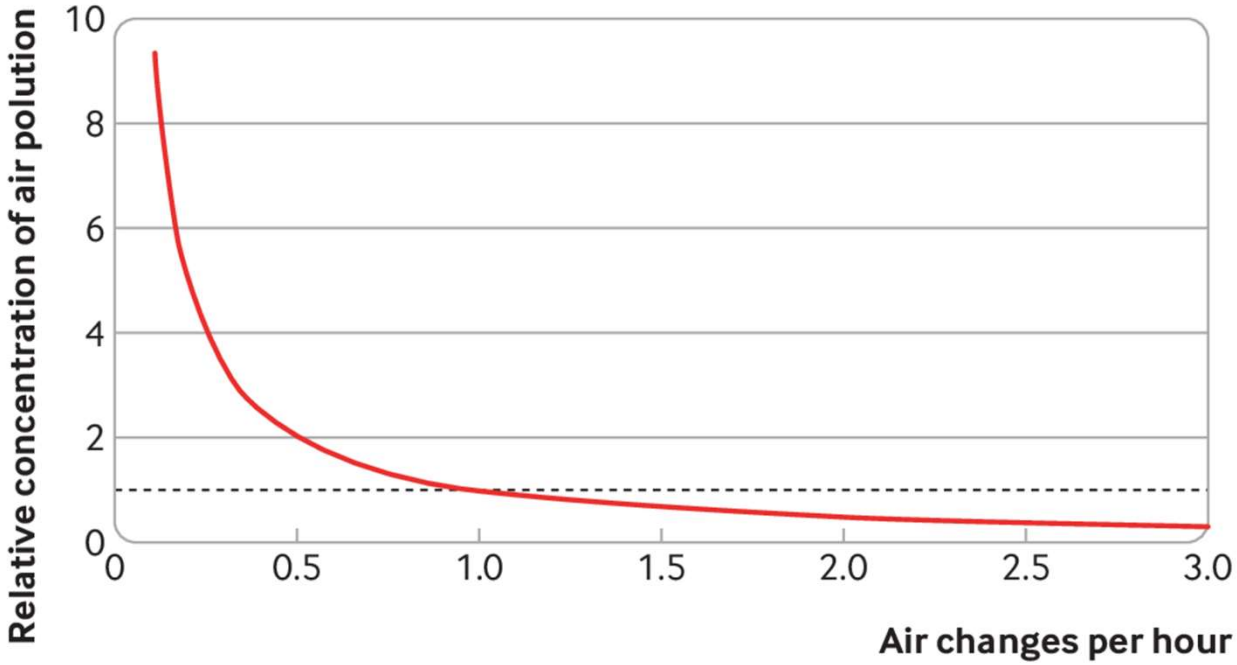


Fig 1 | Change in indoor pollutant concentration as a function of air exchange rate. Relative pollutant concentration=1 at 1 air change per hour (broken line)

Petrou G, et al. Home energy efficiency under net zero: time to monitor UK indoor air *BMJ* 2022; 377 :e069435 doi:10.1136/bmj-2021-069435

NAQTS

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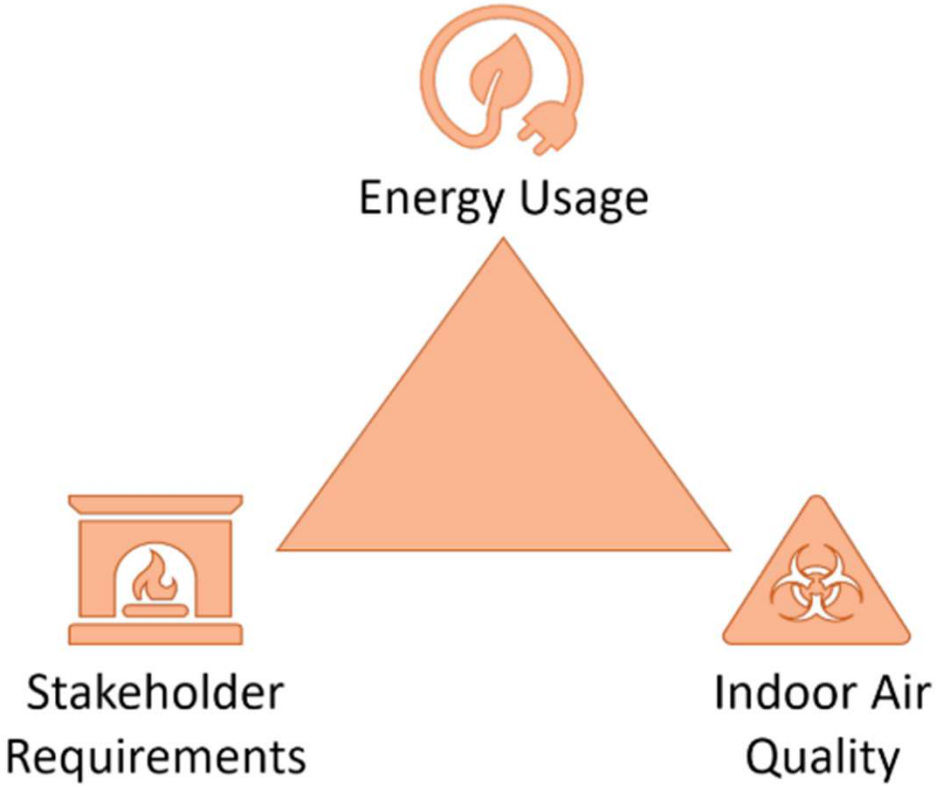
Trilemma?

- Balancing IAQ and Energy is not just about technical fixes
- IAQ-Energy tensions / co-benefits will be mediated by people
- Stakeholder requirements, including:
  - Thermal comfort
  - Social use of the space
  - Socio-temporal structures



Iman Hussain, Adrian Friday, and Douglas Booker. 2023. The Indoor Air Quality Trilemma: Improving Air Quality, Using Less Energy, and Meeting Stakeholder Requirements. In Extended Abstracts of the 2023 CHI Conference on Human Factors in Computing Systems (CHI EA '23). Association for Computing Machinery, New York, NY, USA, Article 275, 1–6. https://doi.org/10.1145/3544549.3585898

Summary

- School indoor air quality is diverse across space and time
- There are lots of factors that affect indoor air quality, including indoor and outdoor sources
- CO_2 a great indicator for ventilation rates, but it is not a proxy for all indoor air quality
- Clear need for more ventilation in school classrooms, BUT…
- We must embrace a holistic and balanced approach to schools that:
  - Maintains energy efficiency to meet low-carbon targets
  - Emphasise ALARA to protect building occupants from poor indoor air quality and airborne virus transmission
  - Considers human behaviour and social practices

Building the Evidence to Improve Ventilation

Join us for an online event to explore how research can support evidence for better ventilation and how this can change practice.

Speakers will focus on studies from a range of settings including schools, homes, businesses and hospitals.

A panel discussion will focus on opportunities and challenges in enabling change.

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