RAMP Task 7 Environmental and aerosol transmission

Paul Linden

Department of Applied Mathematics and Theoretical Physics

University of Cambridge

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Thanks to

- Chris Pain, Imperial – co lead
- Cath Noakes, Leeds – Head of Environmental Modelling Group, SAGE

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- Rajesh Bhagat, Cambridge
- Huw Woodward, Imperial
- Laetitia Mottet, Imperial

Environment and Health

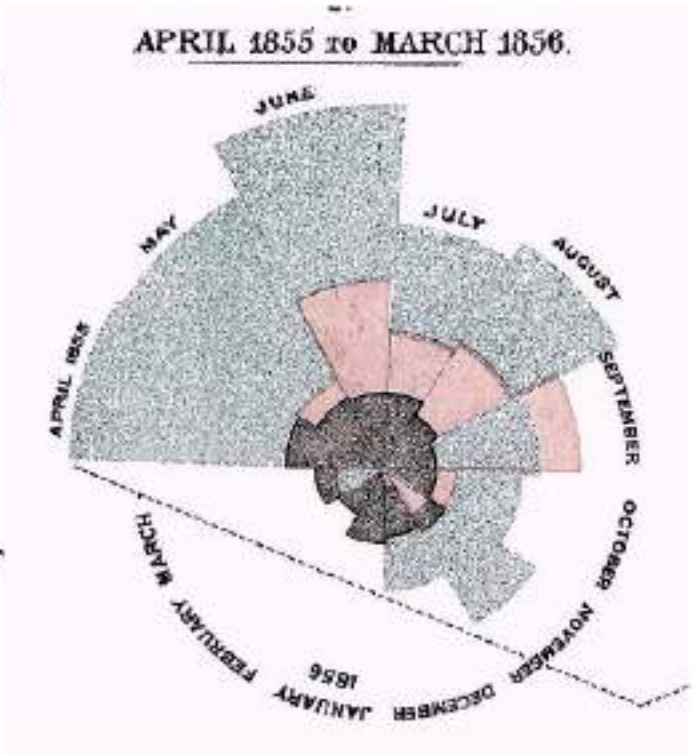
- 1850's: Miasma theory – diseases caused by "bad air"
- 1854: Cholera outbreak in Soho area of London
- John Snow mapped cases and realised geographical significance
- Removal of handle from Broad Street pump stopped outbreak
- Proved Cholera is water-borne

Indoor air and health

".....the very first requirement in a hospital is that it should do the sick no harm"

Florence Nightingale, 1859, Notes on Hospitals

- High ceilings, natural light, ventilation, bed spacing in hospitals
- Social reformer supporting improvemer in sanitary living conditions
- Pioneer of statistical methods



Nightingale rose diagram

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Awareness of respiratory risks

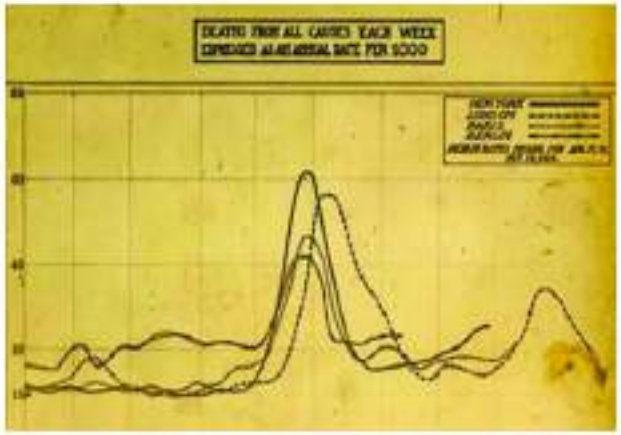
Flugge 1897 - respiratory droplets contain bacteria, settle within 2 m.

It has been found that when the Debating Chamber is in use, the number of bacteria deposited from air leaving the Debating Chamber was increased as compared with the number obtained from corresponding air when the Chamber was empty. The chief bacterial contamination detected in air leaving the Debating Chamber during debates was due to the presence therein of micro-organisms disseminated from the mouth and upper respiratory passages of persons speaking, coughing, sneezing, etc., within the Debating Chamber.

Gordon, House of Commons Ventilation, 1905

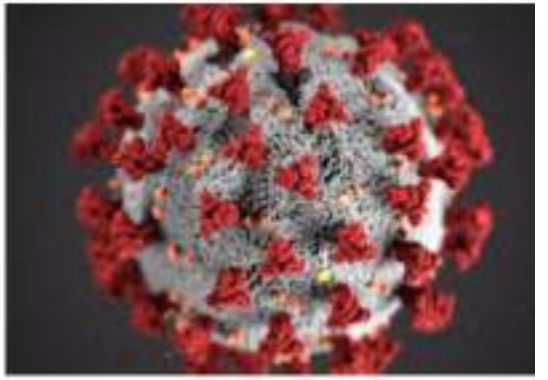
Is Influenza airborne?

- "…mostly occurs in close proximity to the index patient. Hence it is unlikely to be airborne." Brankston et al. Lancet (2007)
- "There is some evidence for airborne transmission of influenza infection. Hence airborne precaution such as N95 masks need to be used". Tellier, EID (2006), NAS (2009)
- EMIT study to compare droplet & aerosol – inconclusive
- Evidence in small aerosol droplets (Milton et al 2013, Yan et al 2018) and in room air samples



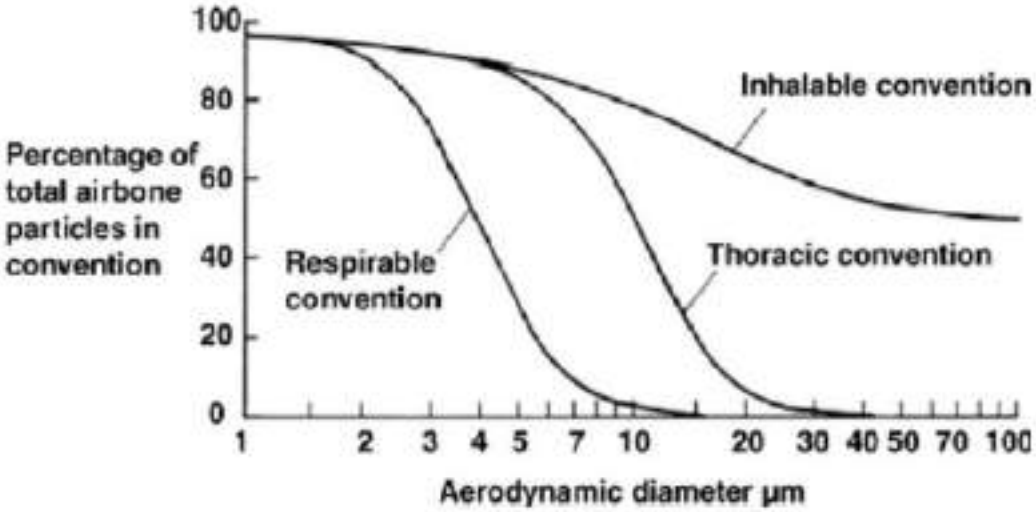
The challenge of SARS-CoV-2

- Small (~100nm) enveloped virus with lipid bilayer
- Highly infectious – Ro (unchecked) around 3
- Evidence that super spreading events play a big role
- Evidence that pre-symptomatic phase is most infectious
- Location & environment matters
    - Household transmission likely dominates
    - Parties, bars, nightclubs, conferences, singing, places of worship
    - Meat processing



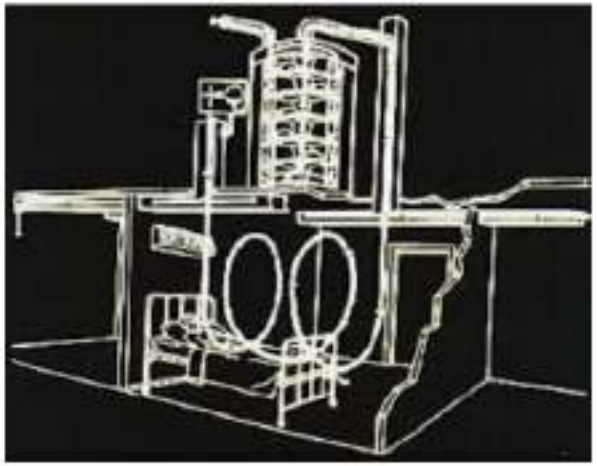
Aerosol or Droplet?

- Infection control refers to <5 μm "airborne", >5μm "droplet"
- Up to 100 μm is inhalable
- Surface/facial contamination can be any size
- Size that matters may depend on disease



Airborne Transmission

- TB suspected airborne disease
- Wells – 1934 proposed concept of a "droplet nuclei"
- Riley and Wells TB Baltimore study – 1958-1962
  - Ward air extracted and passed through guinea pig houses
  - 134 infected over 4 years
  - Proof that TB is airborne
  - Also showed that UV air disinfection is a potential control



RAMP Tasks

- New epidemic models
- Urban analytics
- Human dynamics in small spaces
- Environmental and aerosol transmission
- Within-host modelling
- Co-morbidities
- Structured expert judgement
- Data wrangling

Environmental and aerosol transmission: subgroups

• Exhalation and ventilation	Henry Burridge, Imperial
• Aerosols	Marc Stettler, Imperial
• People movement	Andy Woods, Cambridge
• Deposition on hard surfaces	Marco Felipe King, Leeds
• Inhalation	David Sykes, Glasgow
• Case studies	Prashant Kumar, Surrey

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Focus and strategy

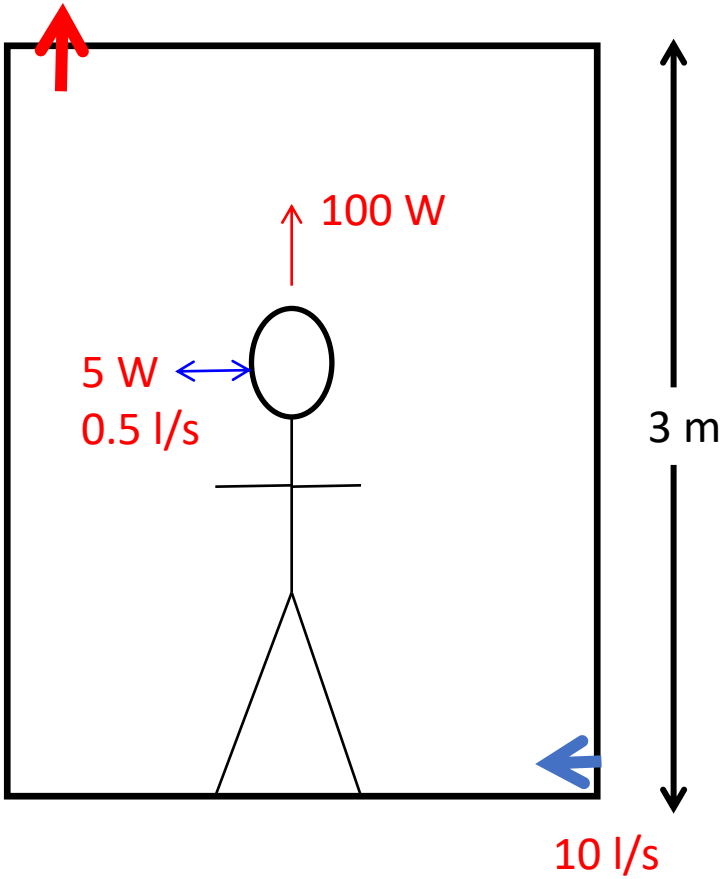
- How can an understanding of the flows within buildings help to mitigate the spread of COVID-19 indoors?

  - Develop key questions to address
  - Investigate key areas
  - Produce and publish guidance/advice

Ventilation and exhalation
key questions

- What are the mechanisms through which building ventilation affects, and could potentially mitigate, the transmission of the coronavirus within the buildings?
- What are suitable separations for social distancing indoors and how do these change with ventilation rates, occupancy levels and activity?
- What advice can be given to building owners/operators/occupants to assess/modify their ventilation during warmer (**colder!!**) weather and how should this advice be delivered?

Some numbers: space 4m x 3m x 3m



Air change rates

N air changes per hour (ACH)

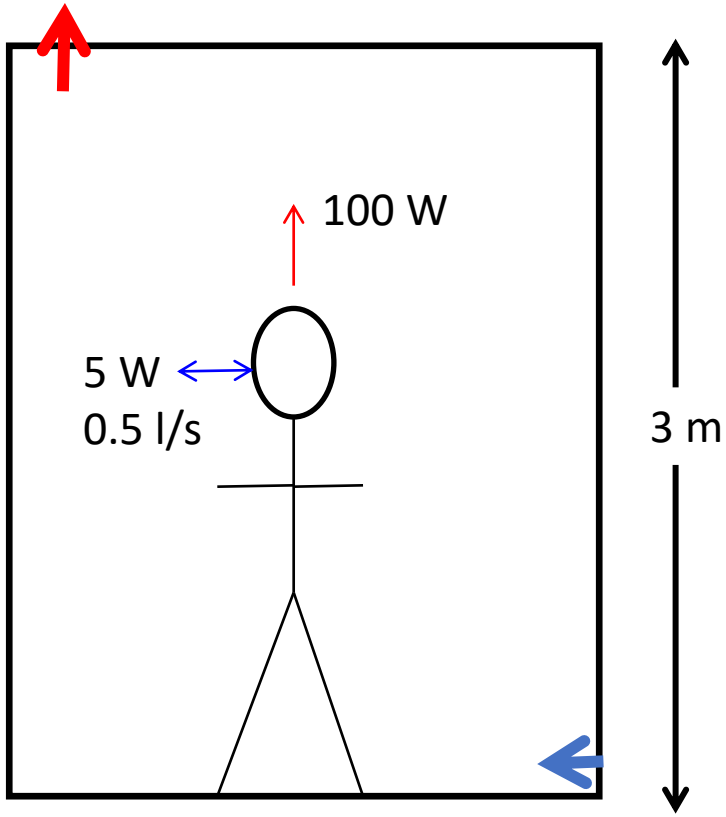
10 l/s = 1 ACH

Volume average flow speed

V = N x height of the room

= 4 mm/s for 5 ACH

= 8 mm/s for 10 ACH



10 l/s = 36 m^3/h

Droplet fall speeds

N air changes per hour (ACH)

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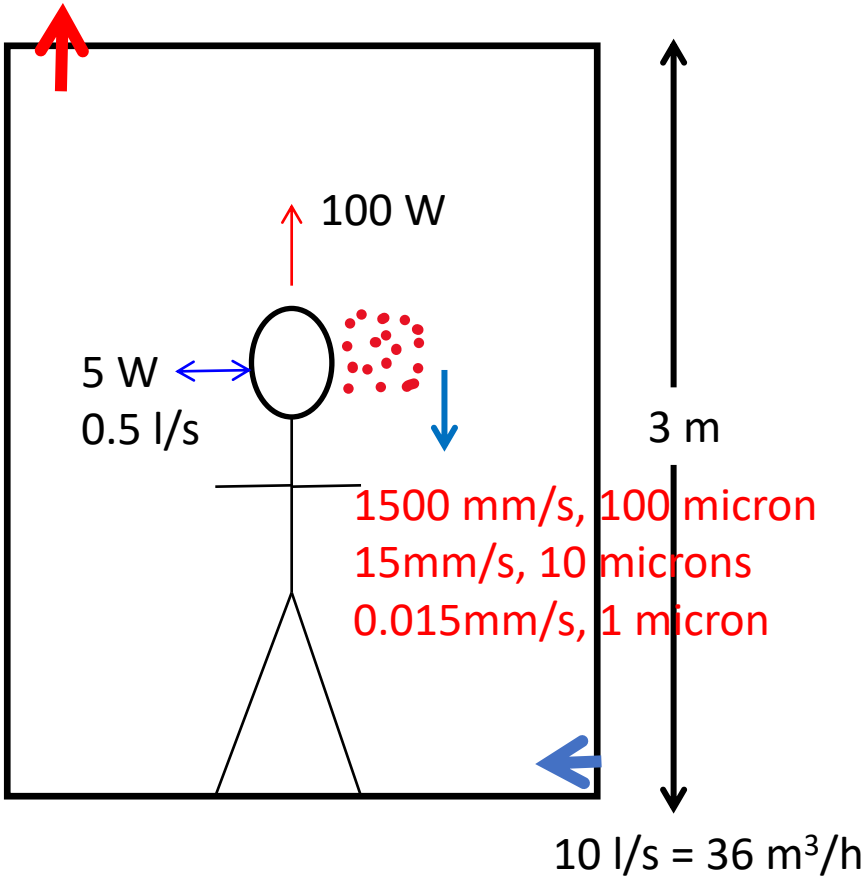
Volume average flow speed

V = N x height of the room

= 4 mm/s for 5 ACH

= 8 mm/s for 10 ACH



Inlet 0.5 m x 0.5 m

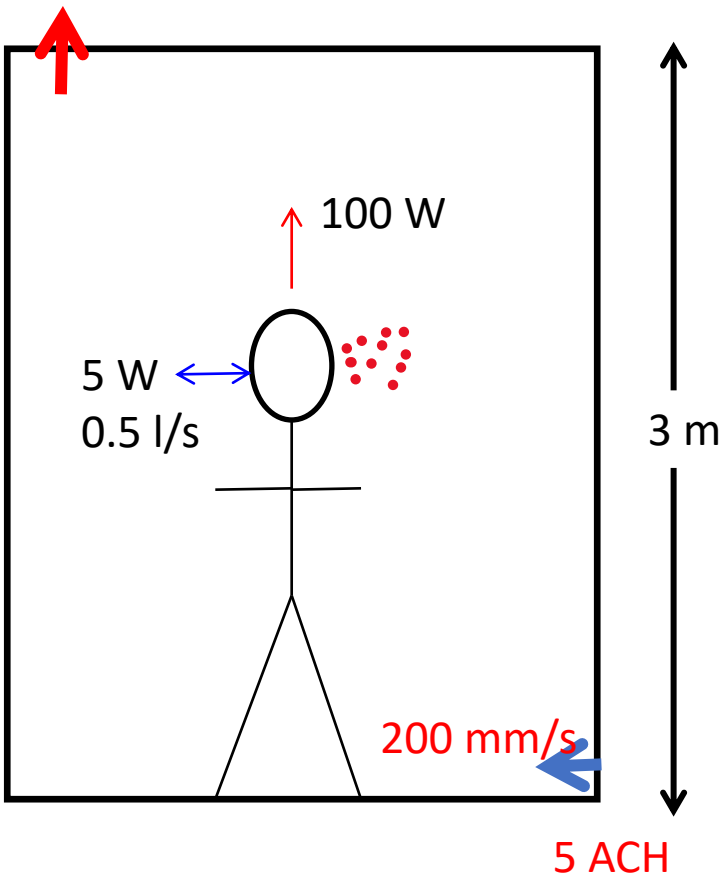
N air changes per hour (ACH)
10 l/s = 1 ACH

Volume average flow speed

V = N x height of the room

= 4 mm/s for 5 ACH
= 8 mm/s for 10 ACH

Droplet fall speeds
1500 mm/s, 100 micron
15mm/s, 10 microns
0.015mm/s, 1 micron



Human plume

Settles et al. 1995 Proc. Intl. Symp. Flow Vis.

N air changes per hour (ACH)
10 l/s = 1 ACH

Volume average flow speed

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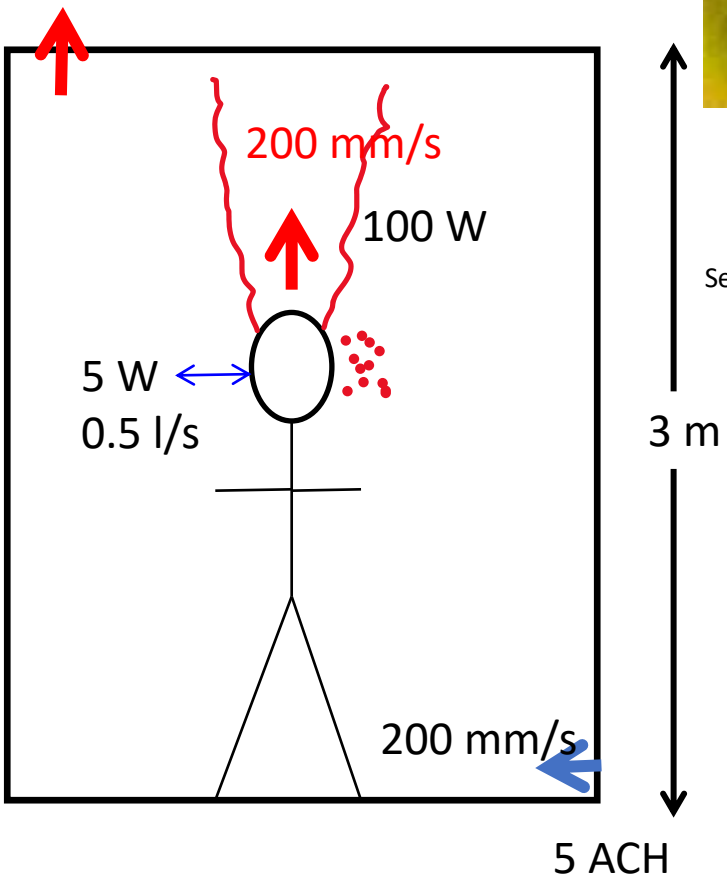

Individual flow elements much more important than the average flow

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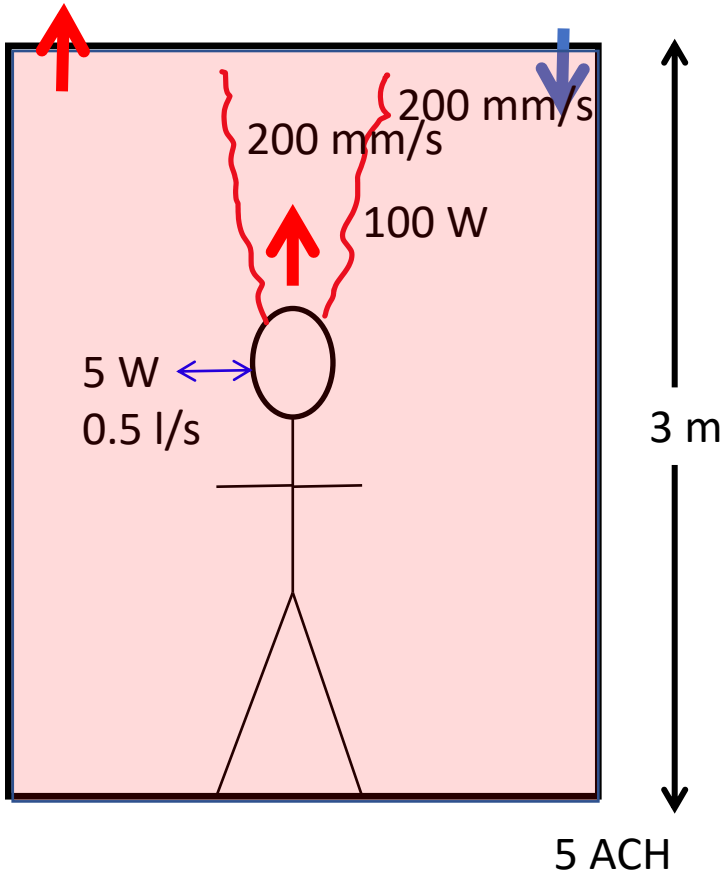
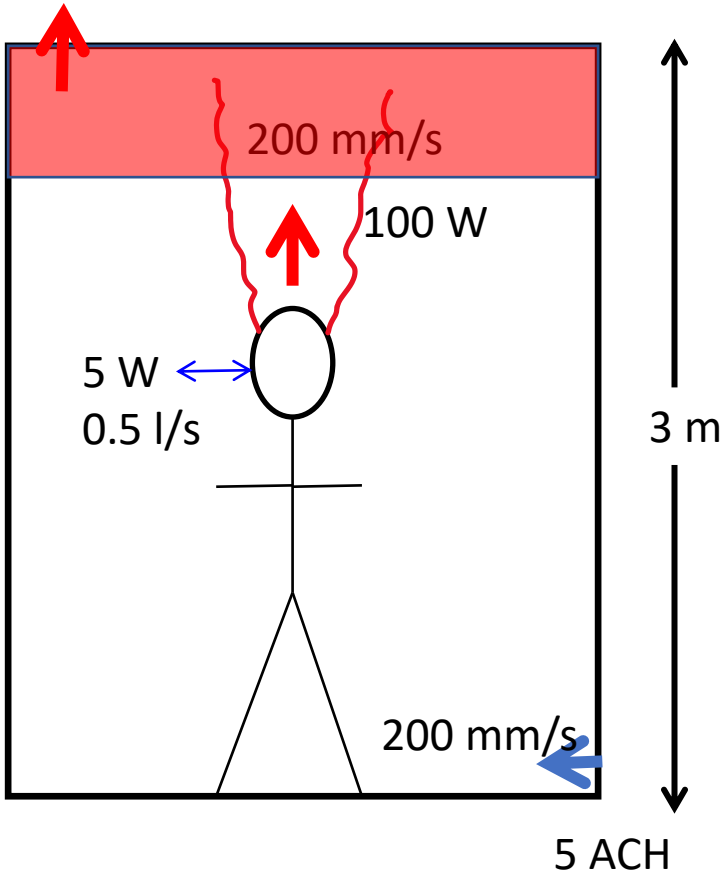
Mixing vs displacement ventilation



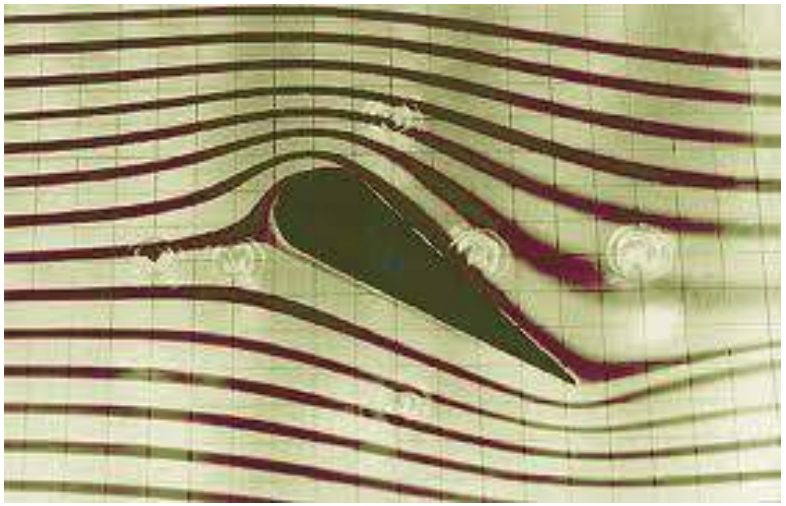


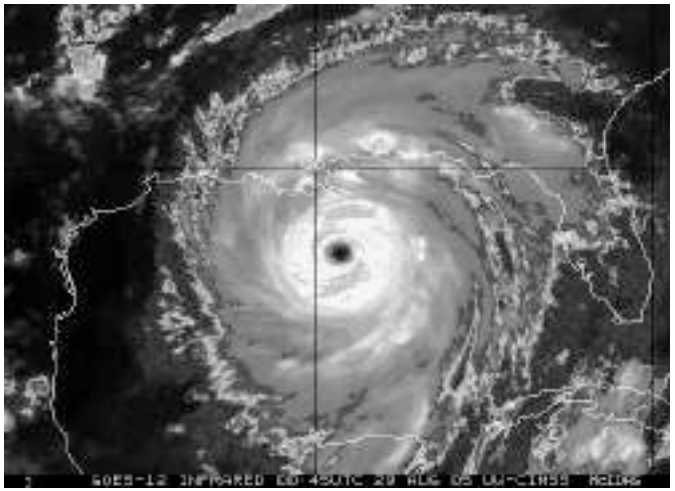
Vent location
Boundary conditions

Displacement

Mixing

Fluid mechanics challenge





Aerospace

boundary conditions

Meteorology

internal dynamics

Currently impossible to compute the full equations without approximation

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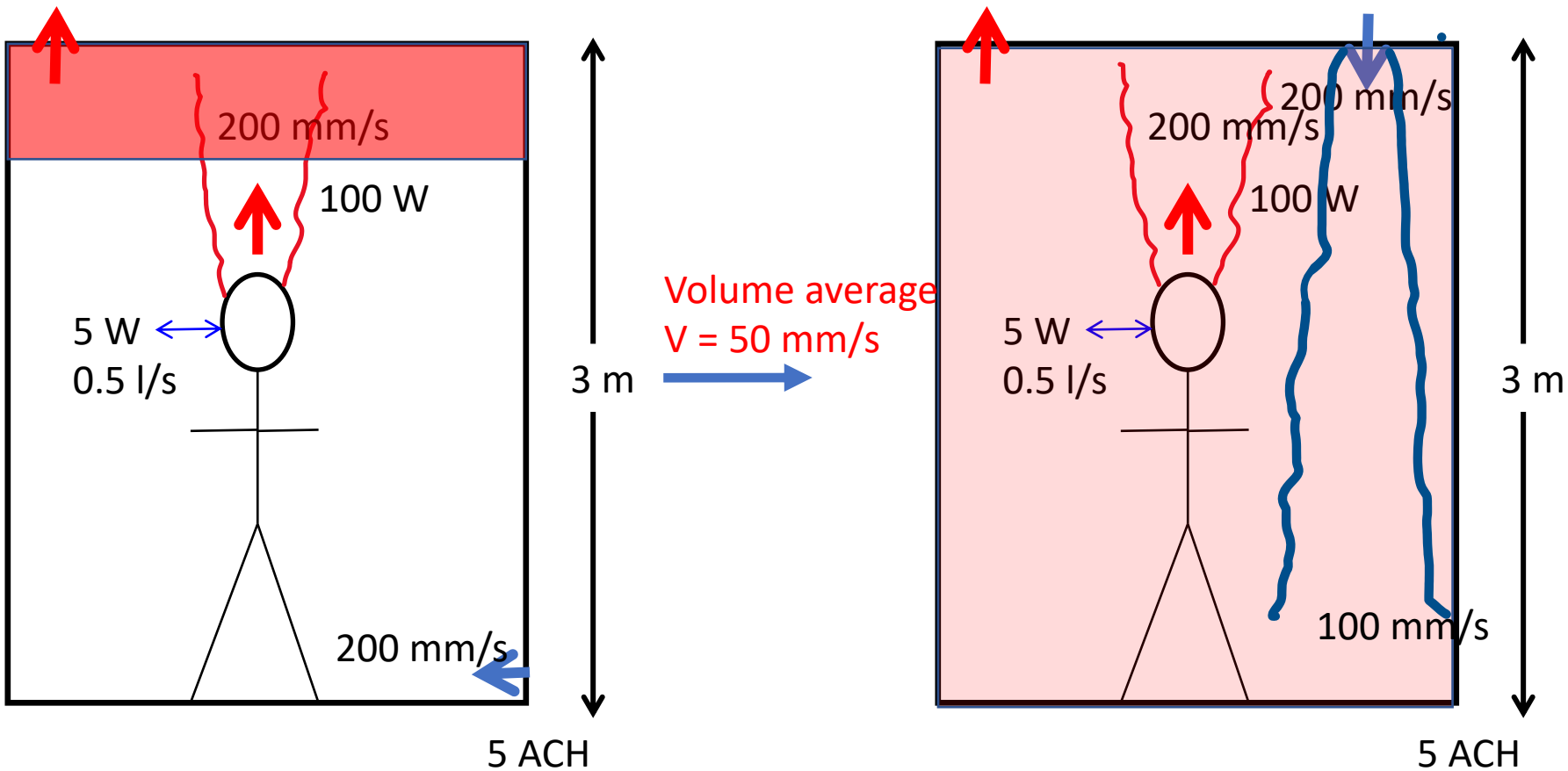
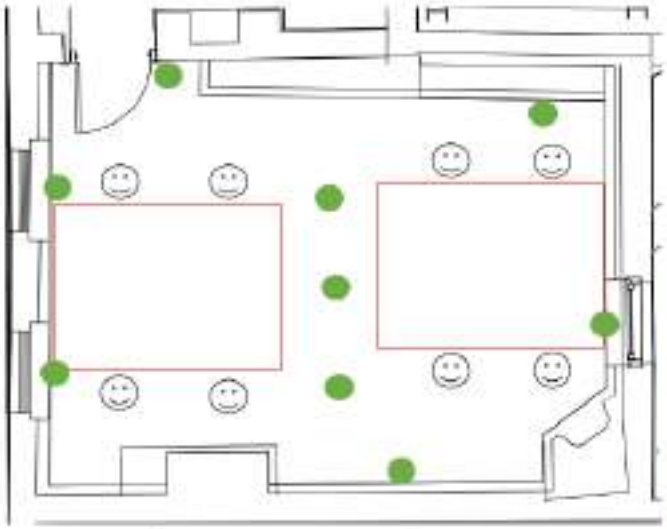
Can we maintain a mixed environment?



Case study room

Sensor Network



Indoor Sensor Network

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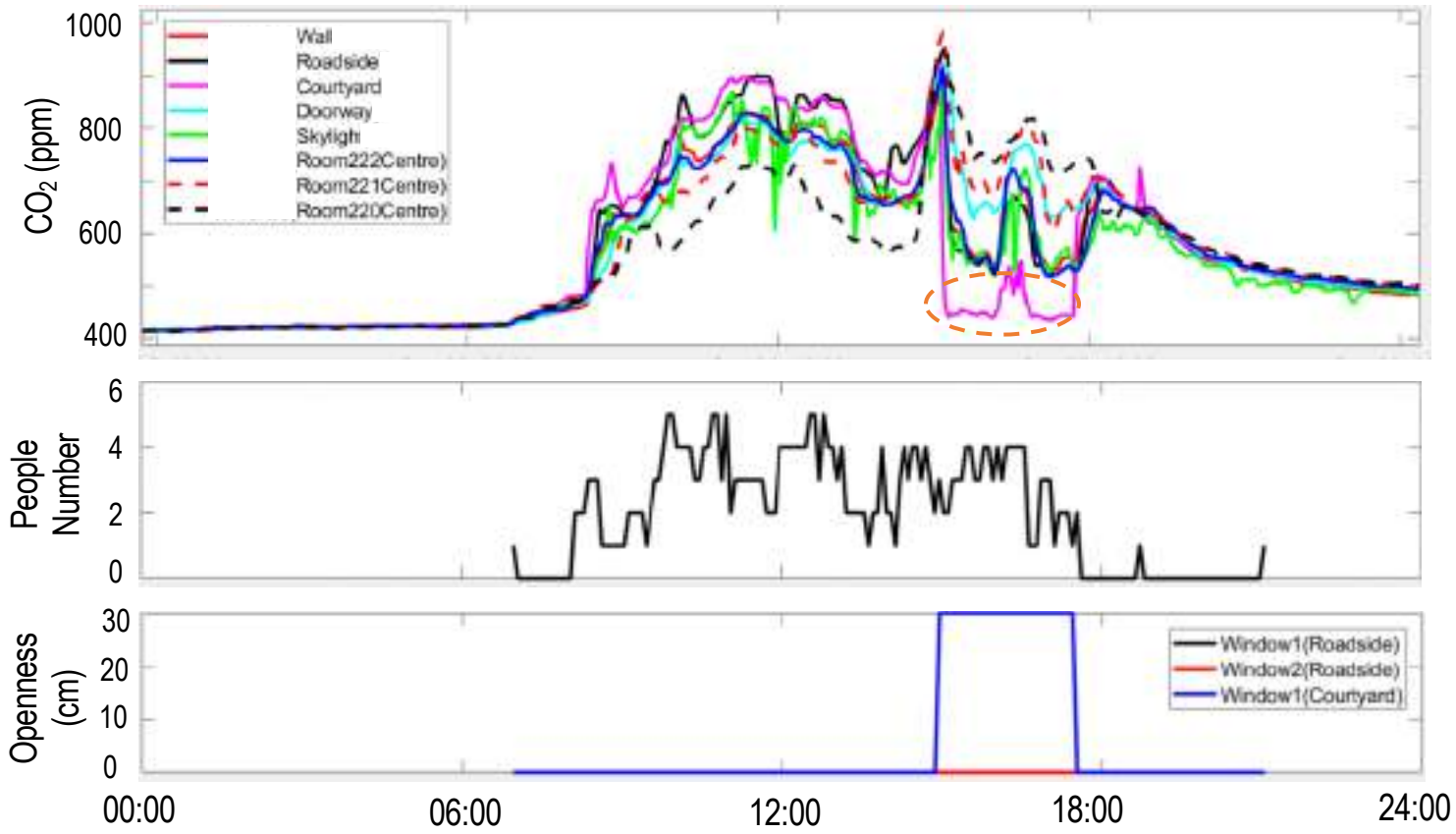
Indoor CO_2 – Single-sided Ventilation



- CO2 highly correlates to the number of occupants in the room
- CO2 reduction is clear when the window is open and CO2 by the window is close to outdoor
- CO2 spatial variation is observed

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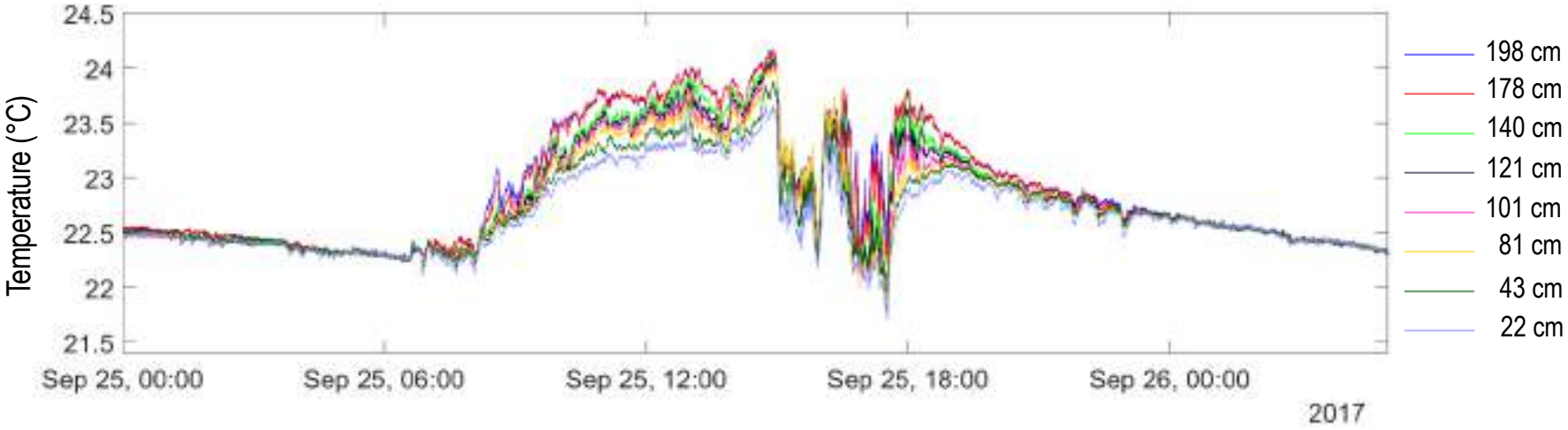
Thermal Stratification



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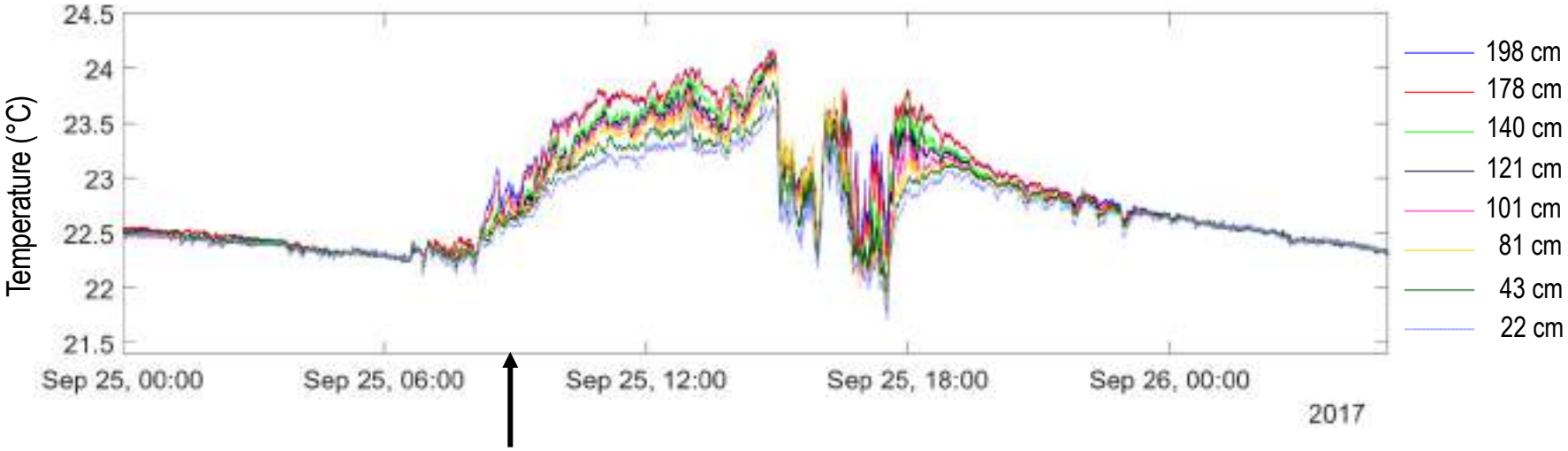
Thermal Stratification



Arrive

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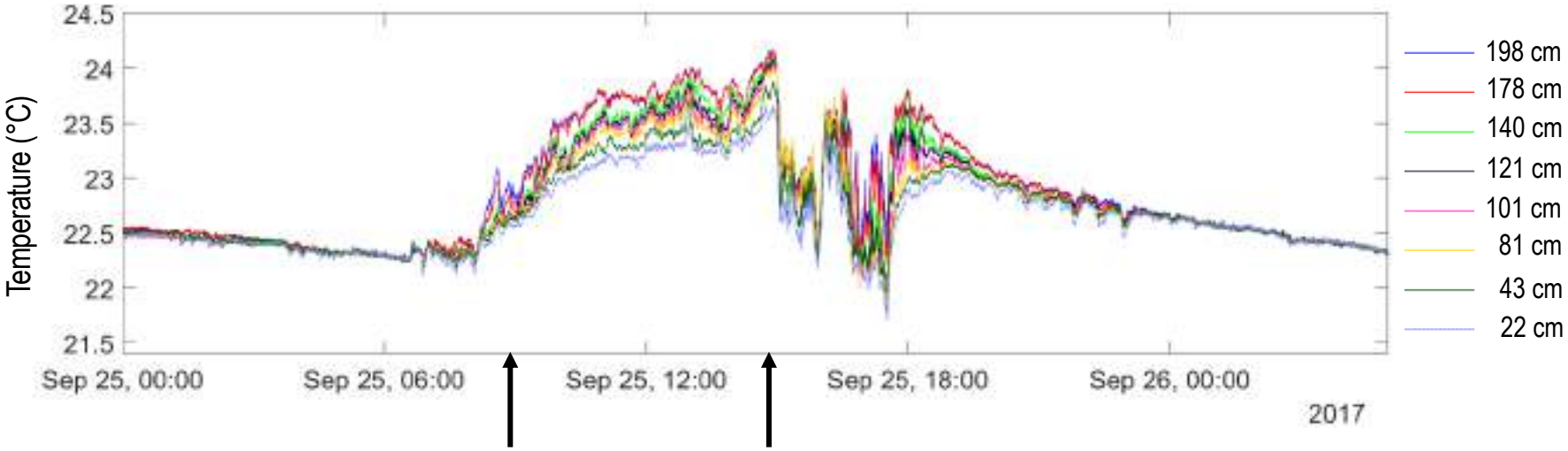
Thermal Stratification



Arrive Lunch

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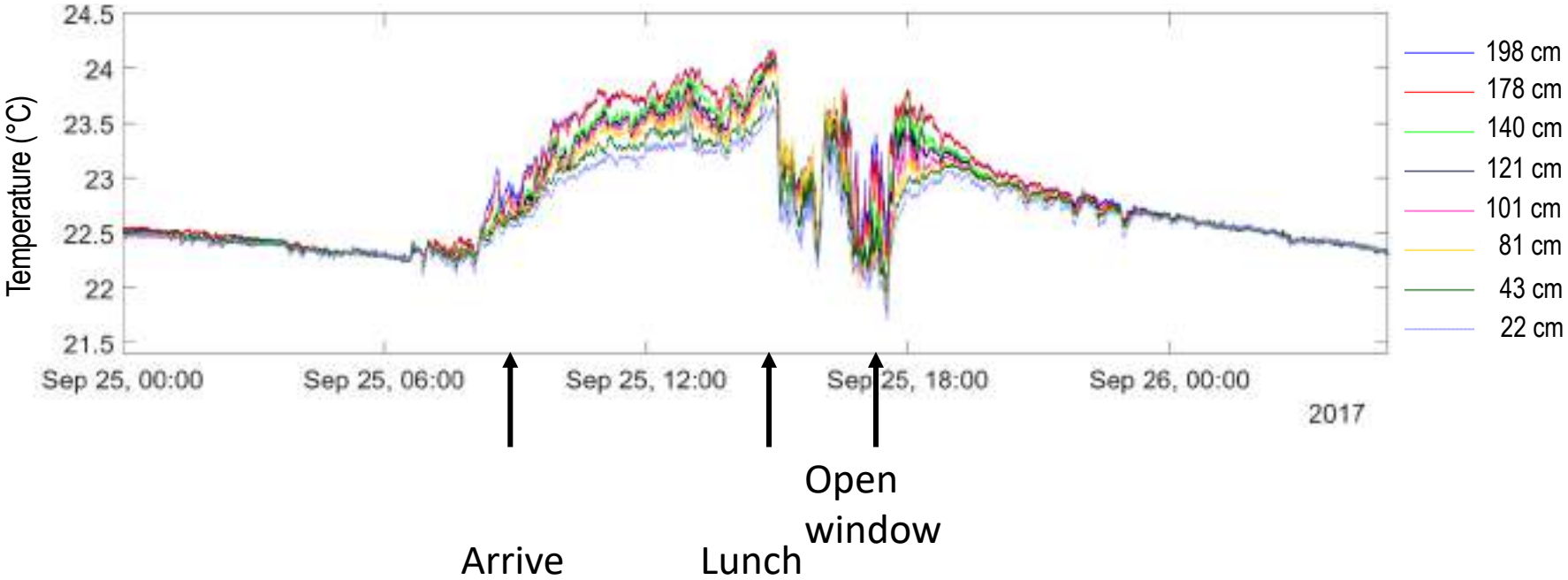
Thermal Stratification



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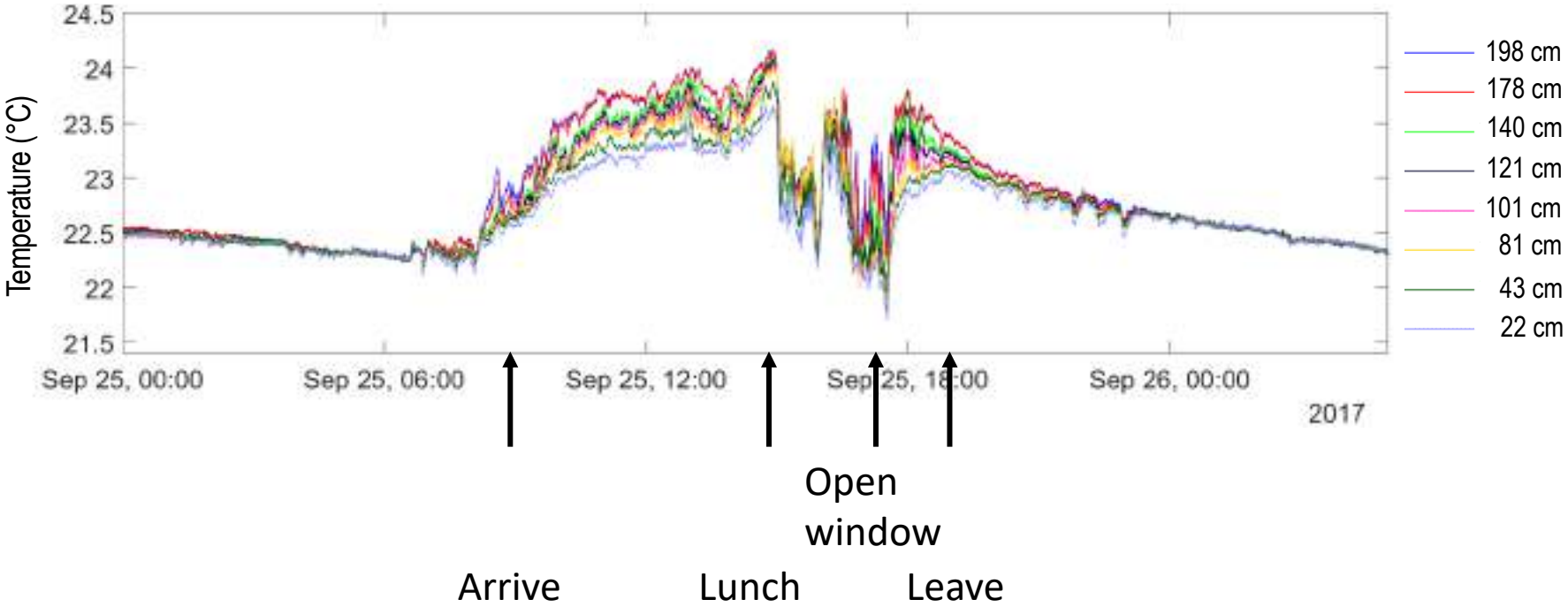
Thermal Stratification



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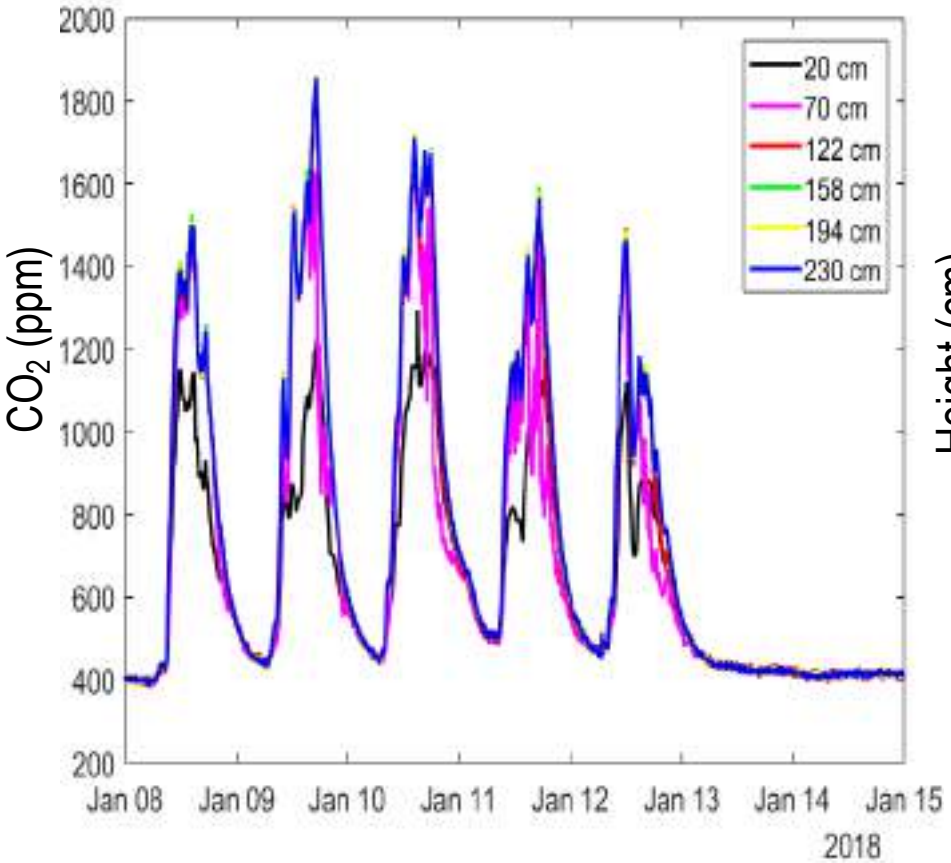
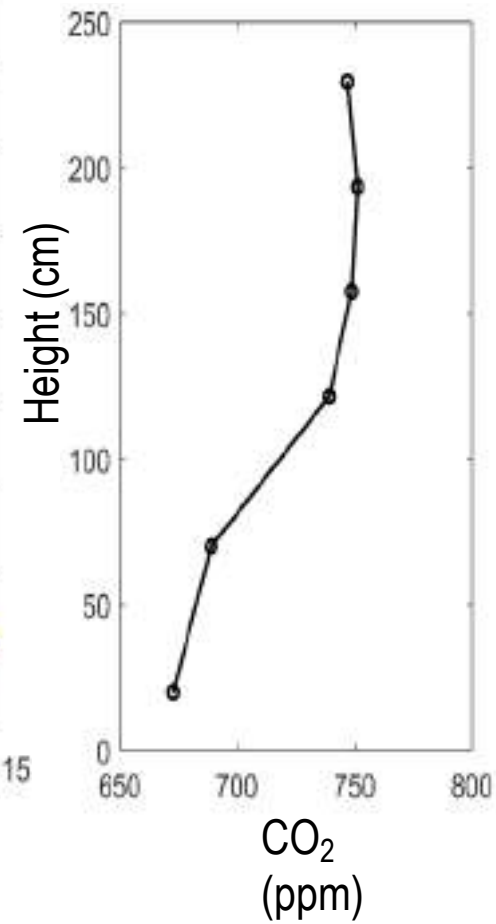
Indoor CO_2 Vertical Stratification





Evidence that breath accumulates near the ceiling

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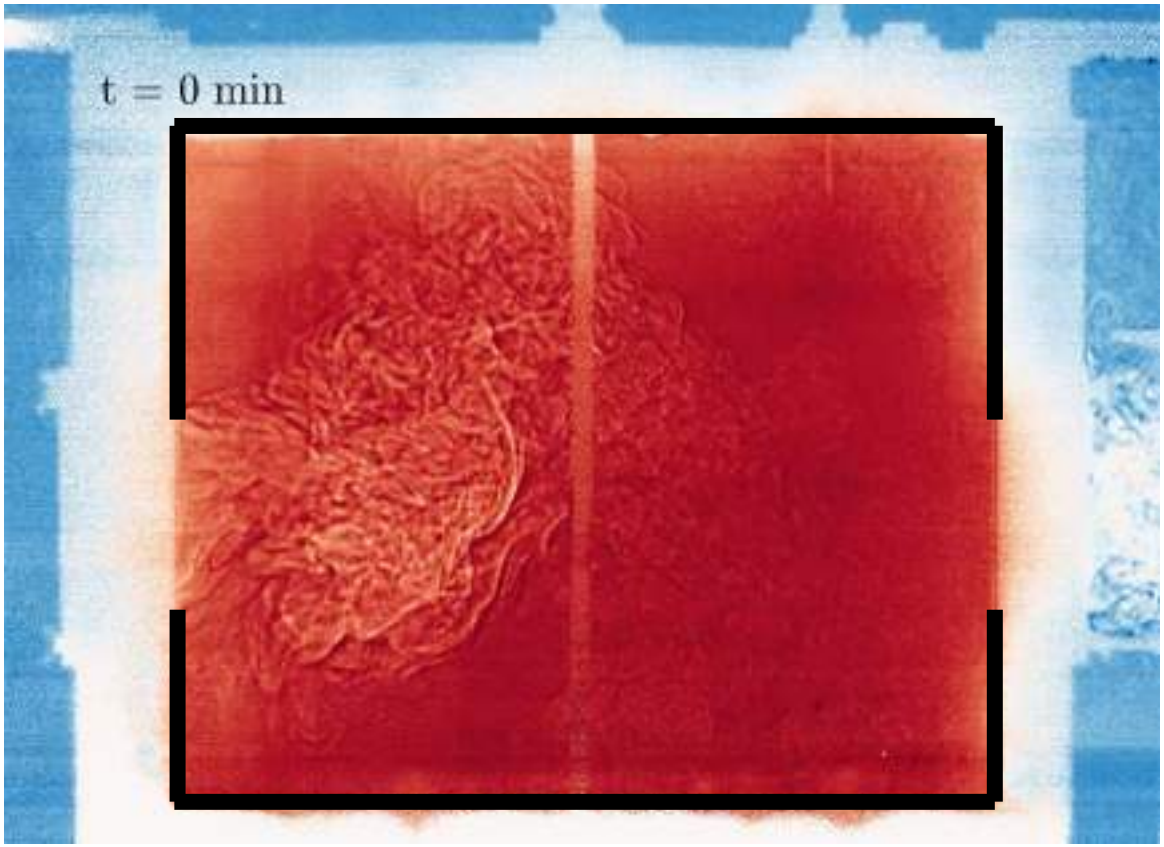
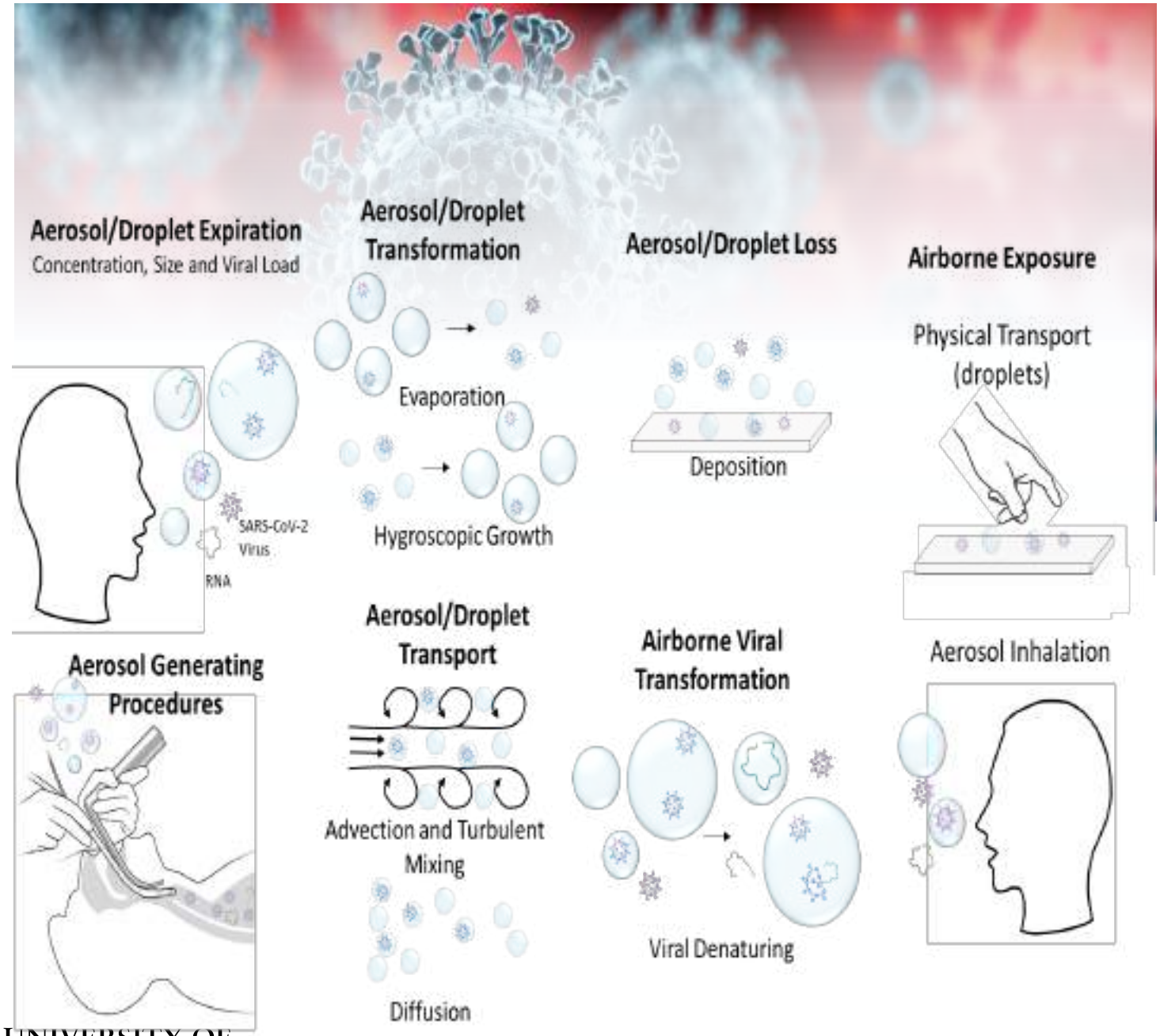
Wind-driven flow



Aerosols: key questions

- What is the size distribution of droplets emitted with speaking, singing, coughing and sneezing?
- How quickly do drops evaporate and what is the residue?
- What is the role of coherent flow structures on droplet transport?



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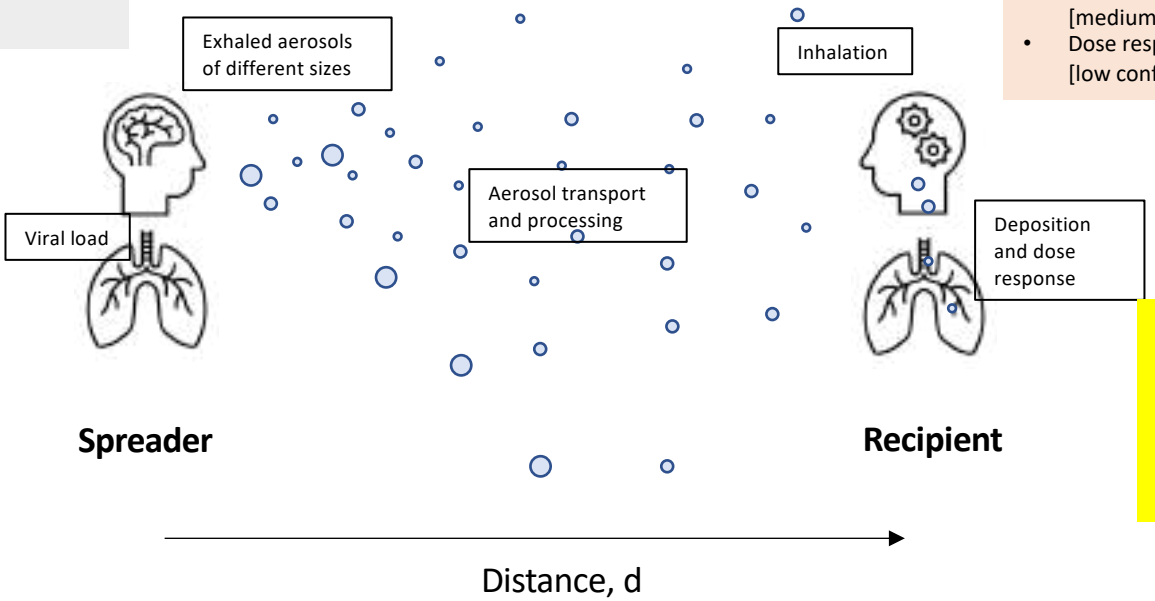
Environmental conditions
- flow and RH
- UV

Exhaled aerosol boundary conditions
- Viral load of spreader [low confidence]
- Exhaled aerosol size distribution [medium confidence]
- Distribution of SARS-CoV-2 in aerosols [low confidence]
- Ventilation rates of spreader and recipient [medium confidence]
- Effect of mitigation, e.g. masks [medium confidence]

Aerosol deposition, transport and evaporation

Quantity of virus present in aerosols of different sizes at point of inhalation

Risk of infection after inhalation depends on:
- Deposition of aerosols in airways [medium confidence]
- Presence of ACE2 in the airways [medium confidence]
- Dose response function [low confidence]



Overall output
- Quantified relative risk of infection for different distances and environmental conditions
- Sensitivity and uncertainty analysis

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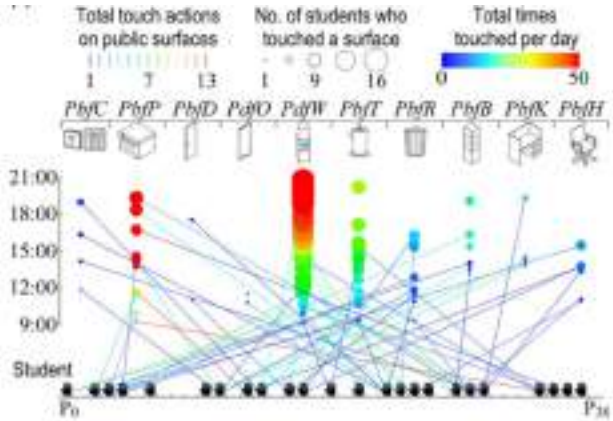
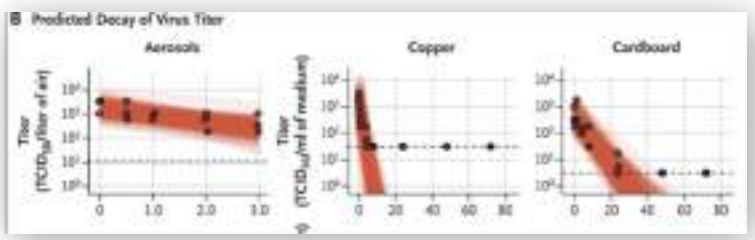
Deposition on hard surfaces: key questions

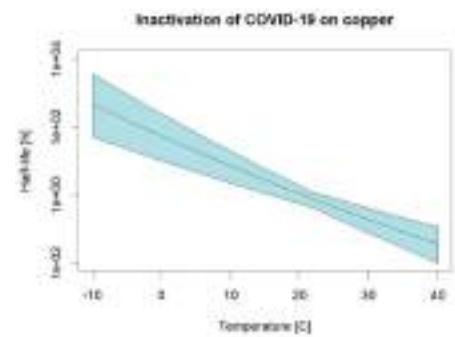
- What are the relevant decay, transmission, and infection rates of Covid-19 in relation to hard surfaces?
- What are the effects of materials and humidity?
- What are the mechanisms involved in human contact?
- How do we optimise cleaning procedures?



A surface touch network in a graduate student office (Zhang *et al.,* 2018)



This figure from Van Doremalen *et al.* (2020) shows decrease in viral concentration as a function of time on different surfaces.



Results from group's statistical analysis to derive additional estimates of Covid-19 half-life dependence on temperature

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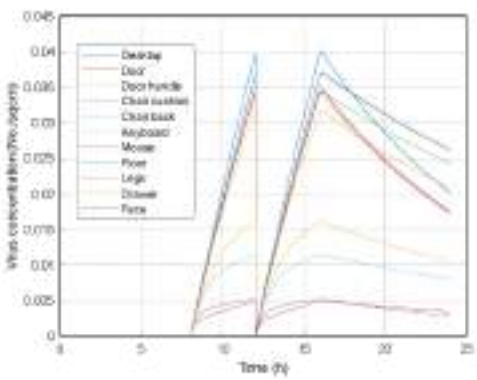
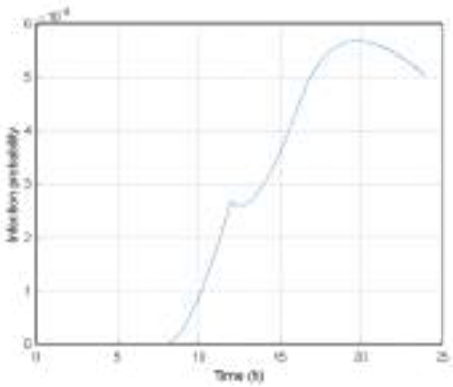
Mathematical modeling of transmission and infection

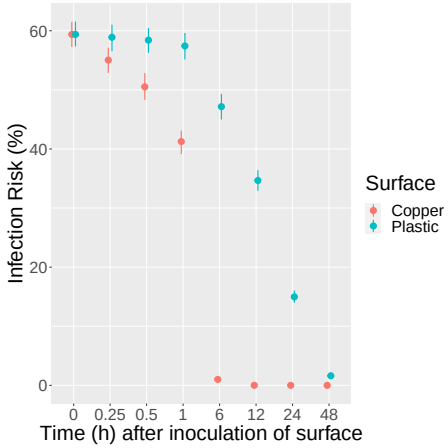
Two concurrent investigations: (i) continuum models of transmission and infection via hard surfaces (ODE models)
(ii) discrete models (contact models with transmission pathway probabilities).





Subject individual in his office from 8:00 to 16:00 + 1 infected individual from 8:00 to 16:00 + cleaning at 12:00

Left graphic shows viral concentration on different surfaces in time; note two maxima of viral concentration due to individuals and cleaning event at 12:00. Right graphic shows example infection probability for this scenario.



Discrete models based on modelling individual touch events, incorporate specific details of how contact occurs and the extent of viral transfer. These models can incorporate specific details of transmission pathways. Typical output of an Monte Carlo simulation shown left for modelling infection risk via copper or plastic.

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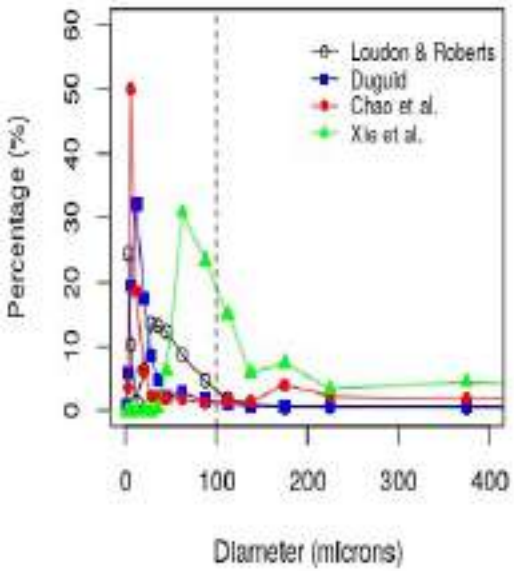
Inhalation: key questions

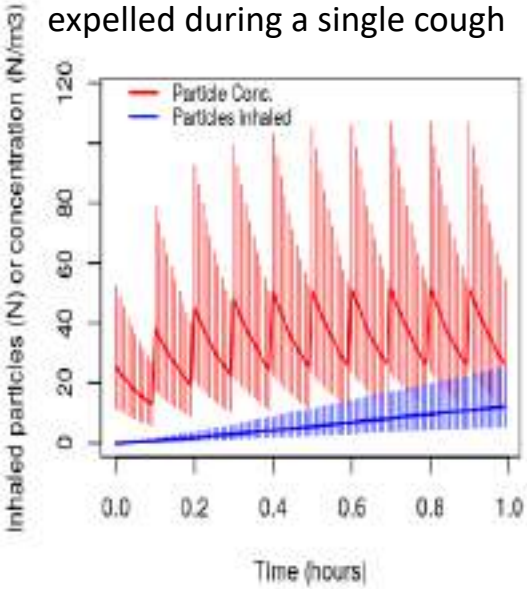
- What advice can be given to building owners/operators/occupants to protect the users of an office (or similar) with regards to face masks or coverings?
- How are aerosols inhaled and over what distance?
- How do we evaluate/measure the effectiveness of PPE?
- How do we evaluate the effectiveness of different face coverings?
- Mouth vs nose: what is the most important route for infection?
- Does the timescale of exposure matter or just the dose?

- On average, 84.9% of droplets from coughing and 88.2% of droplets from speaking have a diameter <100 μm



Droplet diameter distribution expelled during a single cough

- There is a direct correlation between the time that a person spends in the same environment as a carrier, and the likelihood of inhaling the virus



Particle concentration and inhalation from speaking

[4] C Beggs, Is there an airborne component to the transmission of COVID-19? : a quantitative analysis study

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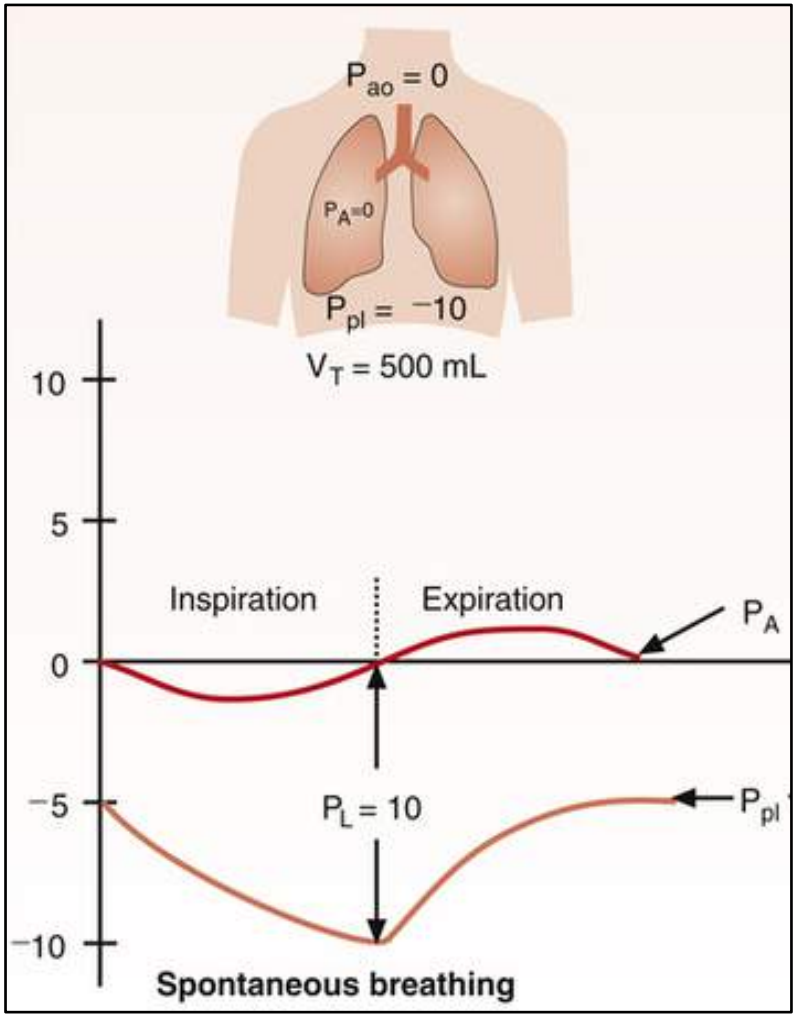

Figure 1: Alveolar (red) and Pleural (Brown) pressure during normal breathing (units cmH_20) [1]

- Negative intrapleural pressure draws 500 ml of air per breath, from a radius of approximately 10 cm around nose and mouth (see Figure 1)
- During breathing fine particles down to 5 μm can be filtered from the air
- A healthy adult inhales on average over 200 litres of air per hour. This volume of air will be in contact with an alveolar surface area of 750 m^2
- This large volume of air, has the potential to carry the viral inoculum
- Before reaching the alveoli within the lungs, it comes in contact with mucosal surfaces in the nasopharynx tract

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[1] A. Mitra , Lecture on Positive Pressure Ventilation

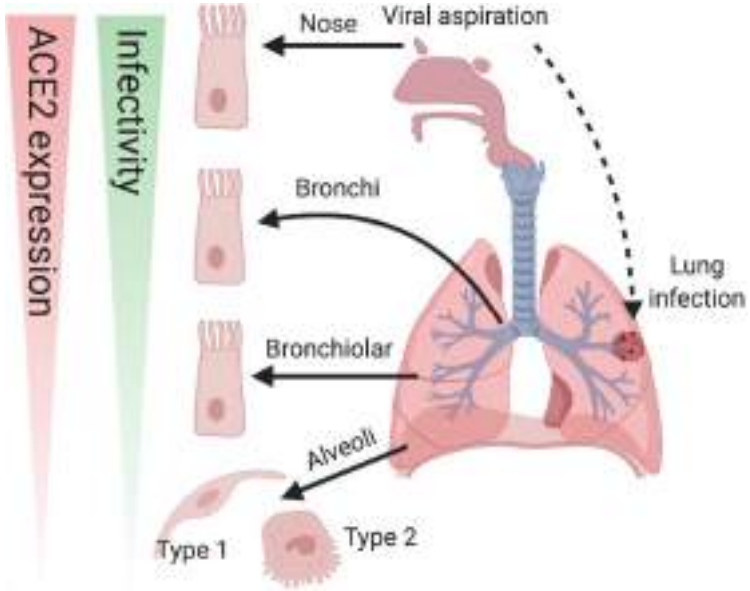

Figure 2: Gradient of infectivity along respiratory tract [2]

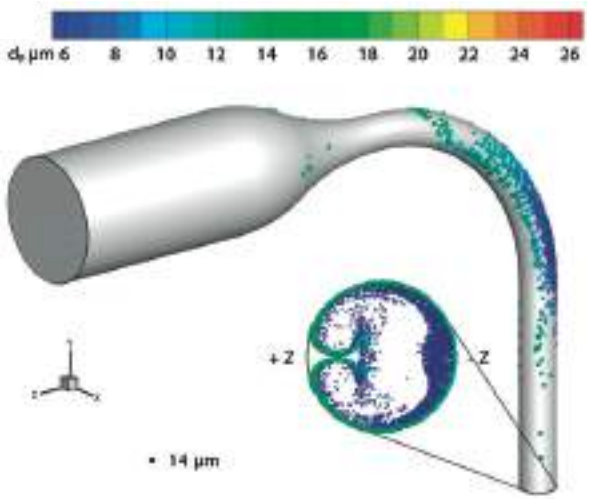

Figure 3: Particle deposition in simplified mouth-throat airways [3]

- SARS-CoV-2 uses the ACE2 receptor, expressed on cell membrane surface of the nose, upper respiratory tract, lungs, arteries, heart, kidney, and intestines to enter into host cells
- SARS-CoV-2 shows a gradient infectivity from the proximal to distal (high to low) respiratory tract (see Figure 2)
- Humidity and temperature, as well as droplet-vapour interaction play an important role in the particle deposition in the upper airways
- Boundary and initial conditions greatly affect the particle deposition in mouth, nose and throat (Figure 3)
- A comprehensive and systematic study on the aforementioned conditions is lacking

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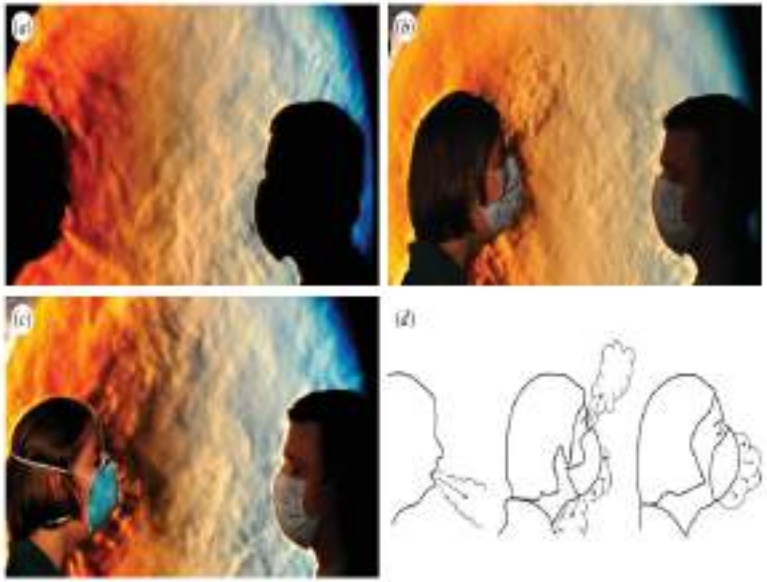
[2] YJ.Hou, SARS-CoV-2 Reverse Genetics Reveals a Variable Infection Gradient in the Respiratory Tract
[3] X Chen, Effects of thermal airflow and mucus-layer interaction on hygroscopic droplet deposition in a simple mouth–throat model

Face masks



Tang et al. 2009 J. R. Soc. Interface

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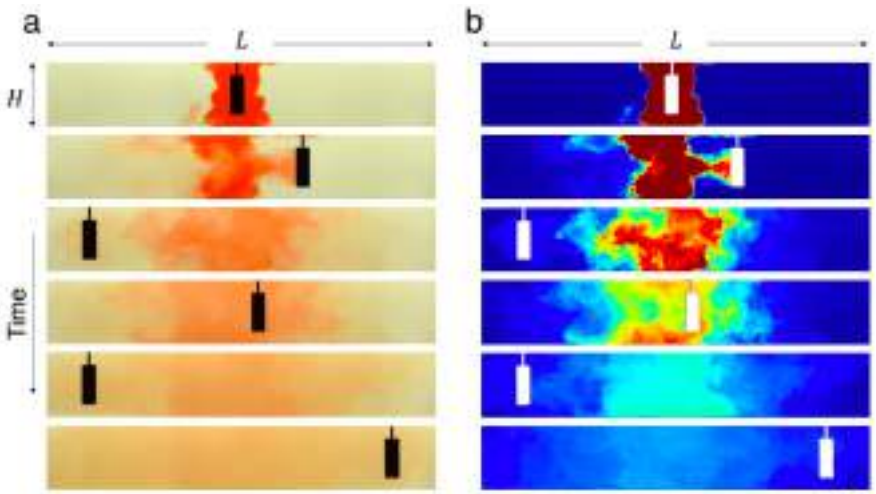
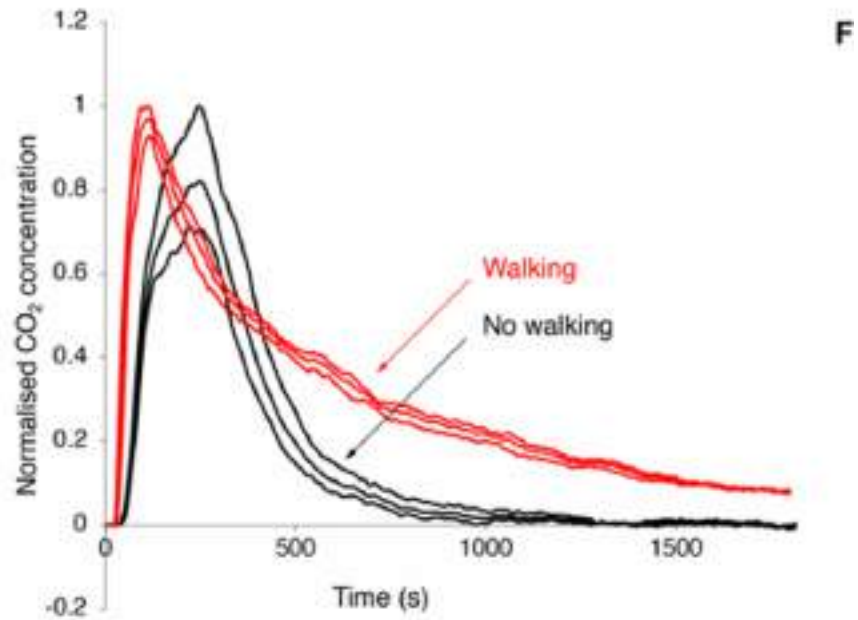
People movement: key questions

- What are the flows induced by the movement of people in buildings?
- How important are the wakes of people in stirring the air?
- How important are the wakes of people in re-suspending deposited droplets?
- What are the timescales associated with the entrance and exit of occupants in a space?

Spread of tracer along a corridor by the wakes of walking people

Courtesy of Andy Woods





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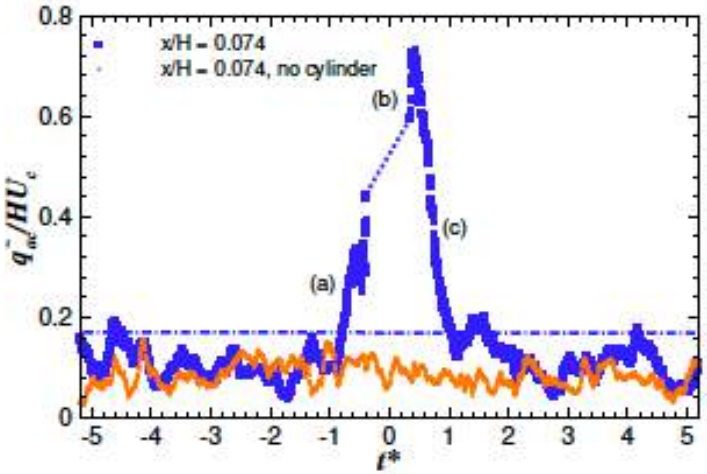
Person walking through an air curtain



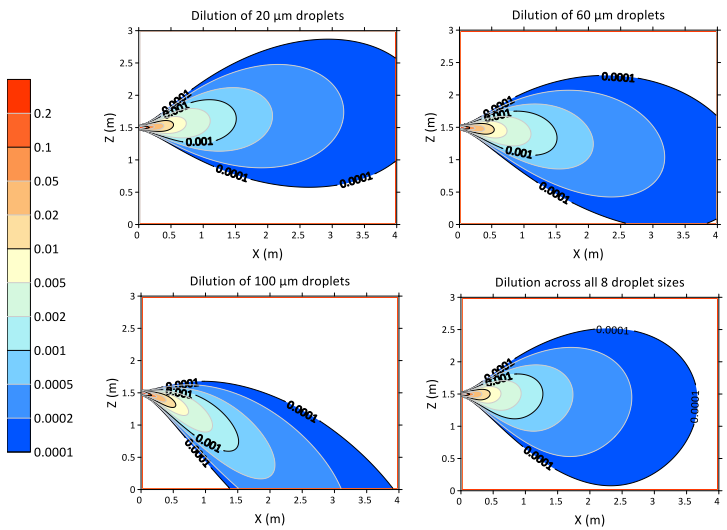
Jha et al. 2020 B&E

Modelling capabilities and case studies: key questions

- What are our current capabilities of modelling environmental transport?
- How well validated are these models?
- What case studies are needed to gain confidence in the models?

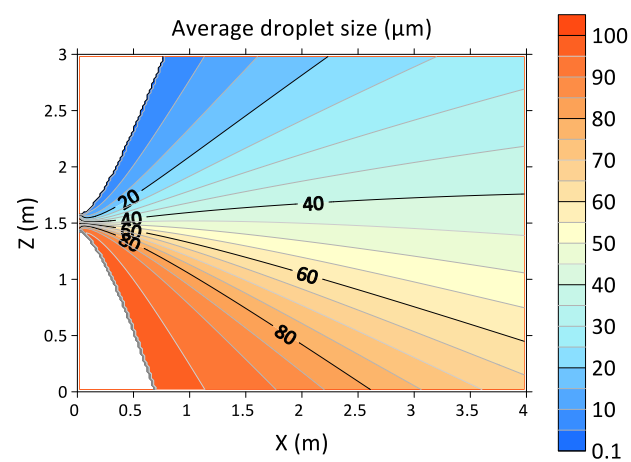
Outdoor droplet dispersion, deposition and evaporation with ADMS jet model (CERC)

- Release velocity 1.5 m/s
- Release height 1.5 m
- 0.3m/s flow; rms turbulence 0.1m/s
- Source diameter 1.5cm
- Temperature 290K
- Relative humidity 50%



Drop sizes after 1 and 5 seconds

d(initial) µm	d (1s) µm	d (5s) µm
2.5	<1	<1
10.0	<1	<1
20.0	15.0	<1
30.0	26.9	5.1
40.0	48.2	26.9
60.0	58.5	52.2
80.0	78.9	74.3
100.0	99.1	95.5



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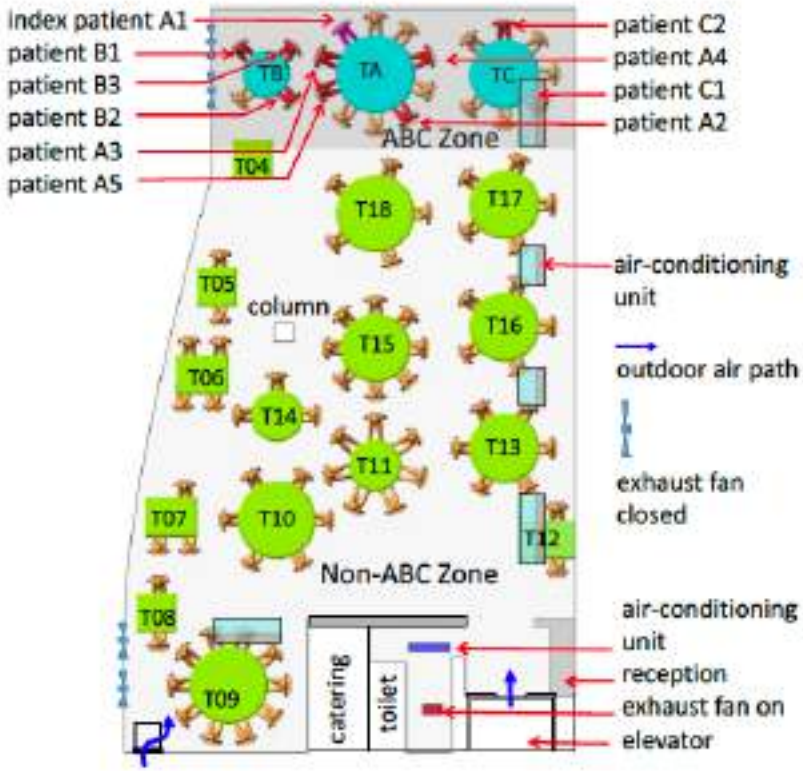
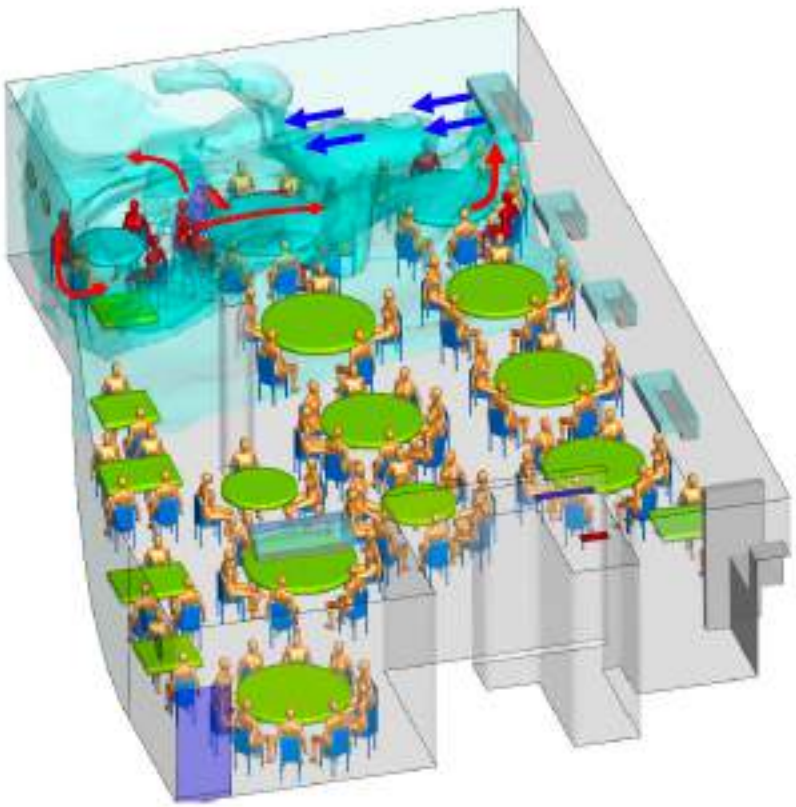
Exhaled breath as a passive scalar





Li Y. et al. 2020 medRxiv.org

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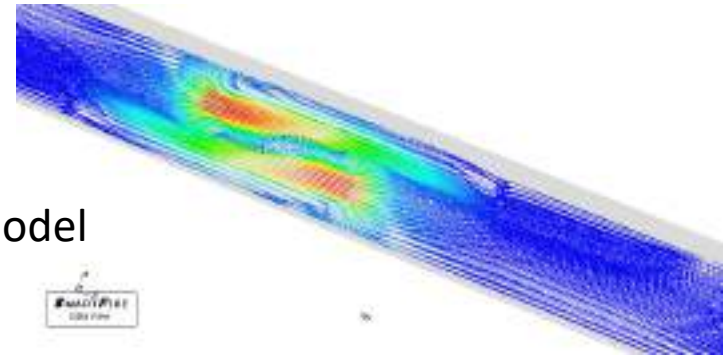
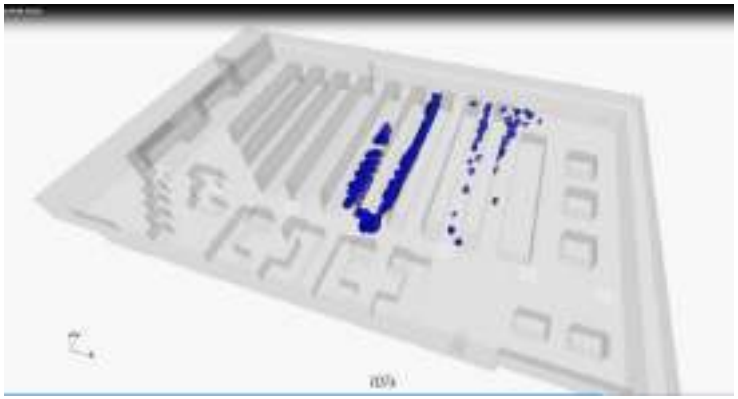
SMARTFIRE: Ed Galea, Greenwich

RANS flow model





Supermarket

Agent based model

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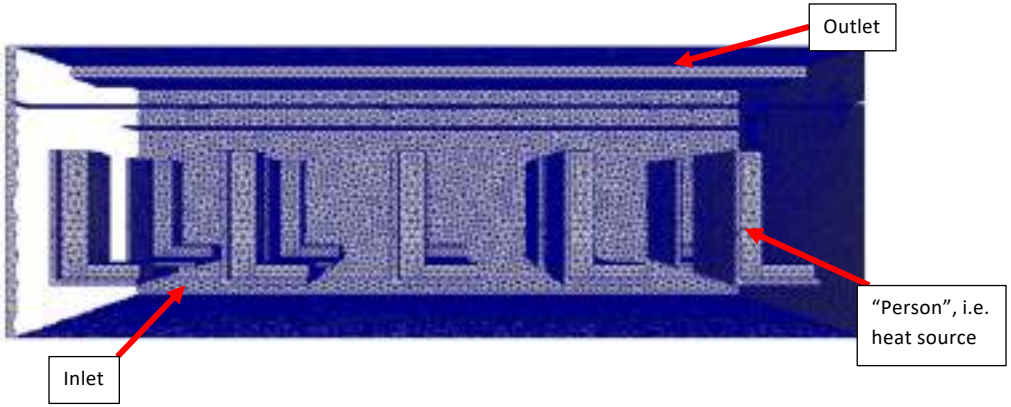
Simulation of dispersion on a train carriage Fluidity (Imperial)

- Simulation of dispersion of passive tracer on a train carriage.
- Heat sources included to account for passenger heat (50W/m^2).
- Inlet at bottom of carriage, outlet at the ceiling.
- Periodic boundary conditions applied at each end of 6.66m long carriage section. Therefore opening and closing of doors not accounted for, no open windows and no people movement.
- Simulation repeated with screens between each row of seats.



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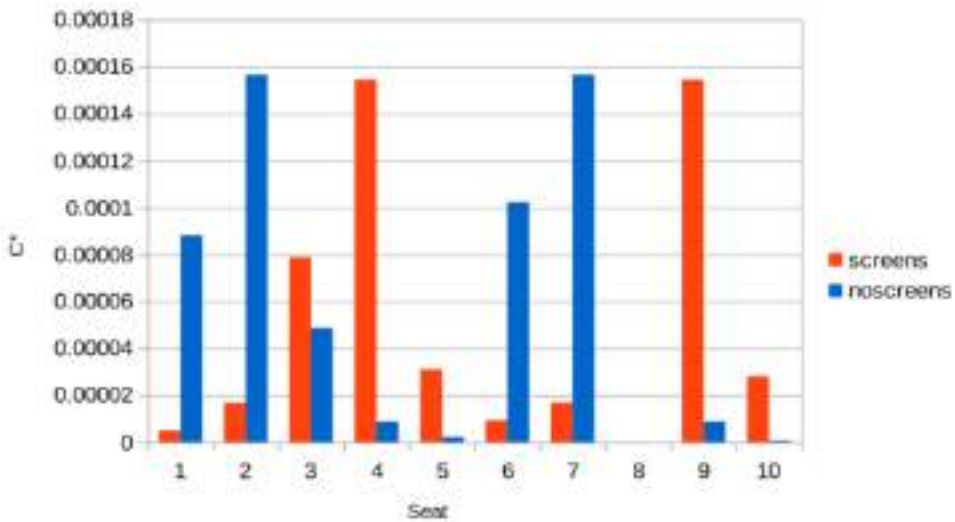
Simulation of dispersion on a train carriage

No screens

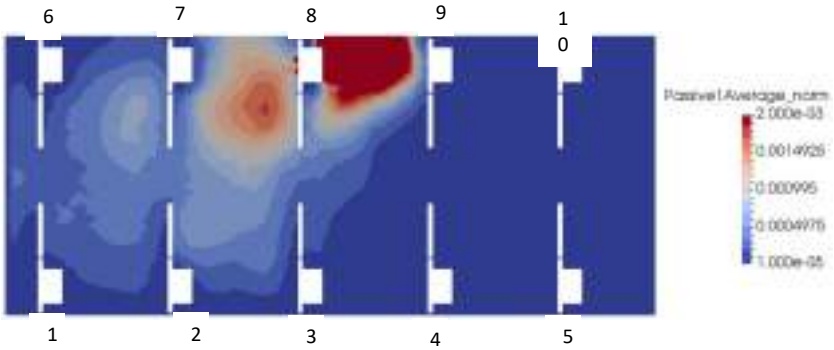
Screens

Simulation of dispersion on a train carriage

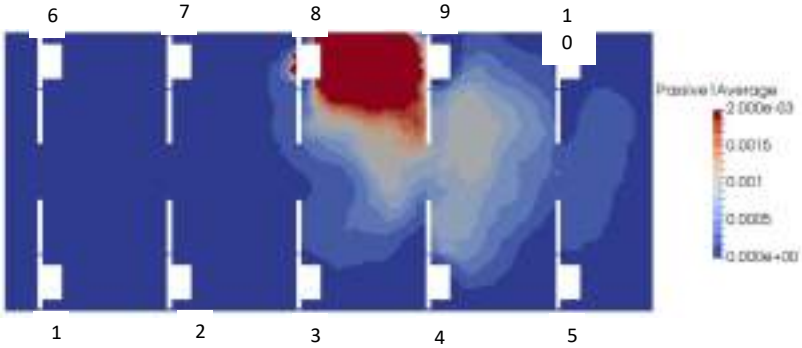
- Average exposure concentration for all passengers:
  - Without screens: 6.4E-5
  - With screens: 5.5E-5



No screens



Screens



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Closing thoughts

- Many faceted problem with many unknowns
  - Viral load in droplets
  - Amount required for infection: over what time scales?
  - Currently only able to discuss relative risk
- Modelling approaches
  - Small scale laboratory and wind tunnel experiments
  - Agent based models
  - Computational models of varying complexity
- General principles
- Applications to wider issues including pollution and air quality: 'Tackling Air Pollution at School' TAPAS

With thanks to

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