The challenge of simulating airflow in buildings: lessons from oceanography to aerospace

Paul Linden

Department of Applied Mathematics & Theoretical Physics

University of Cambridge

UNIVERSITY OF CAMBRIDGE

Urbanisation

*by 2050 75% will live in cities

SHIBUYA, TOKYO | © SHUTTERSTOCK

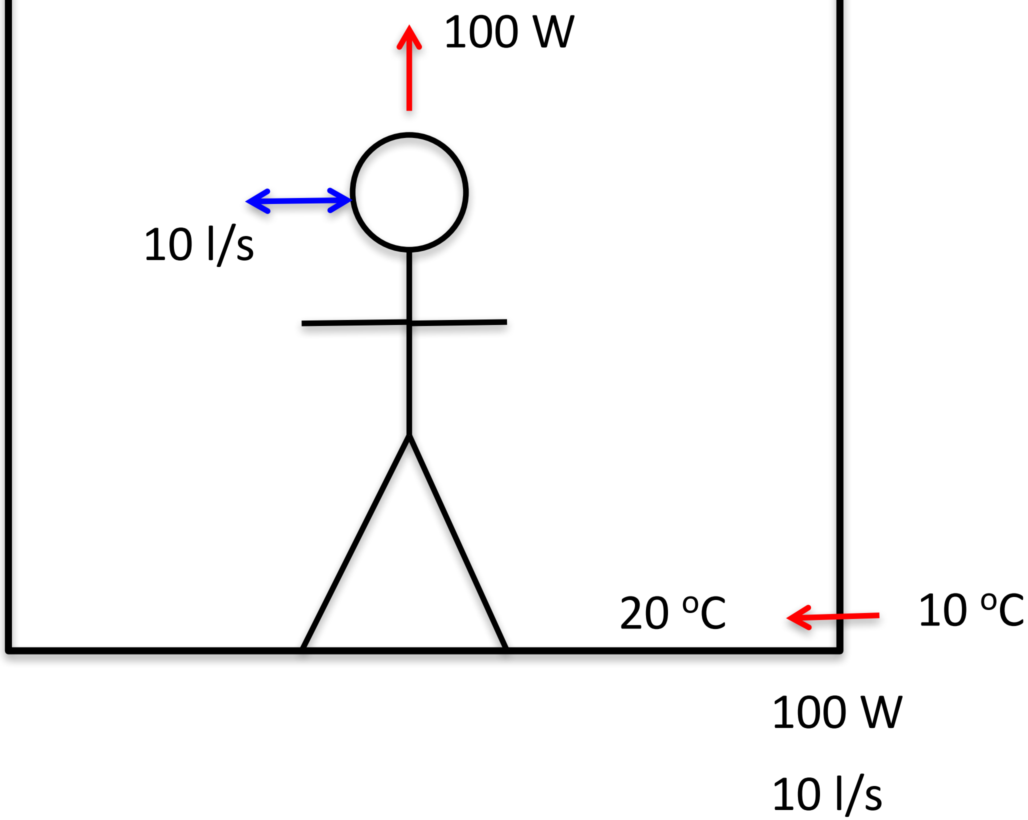
* UNITED NATIONS – WORLD URBANISATION PROSPECTS (2010)

UNIVERSITY OF CAMBRIDGE

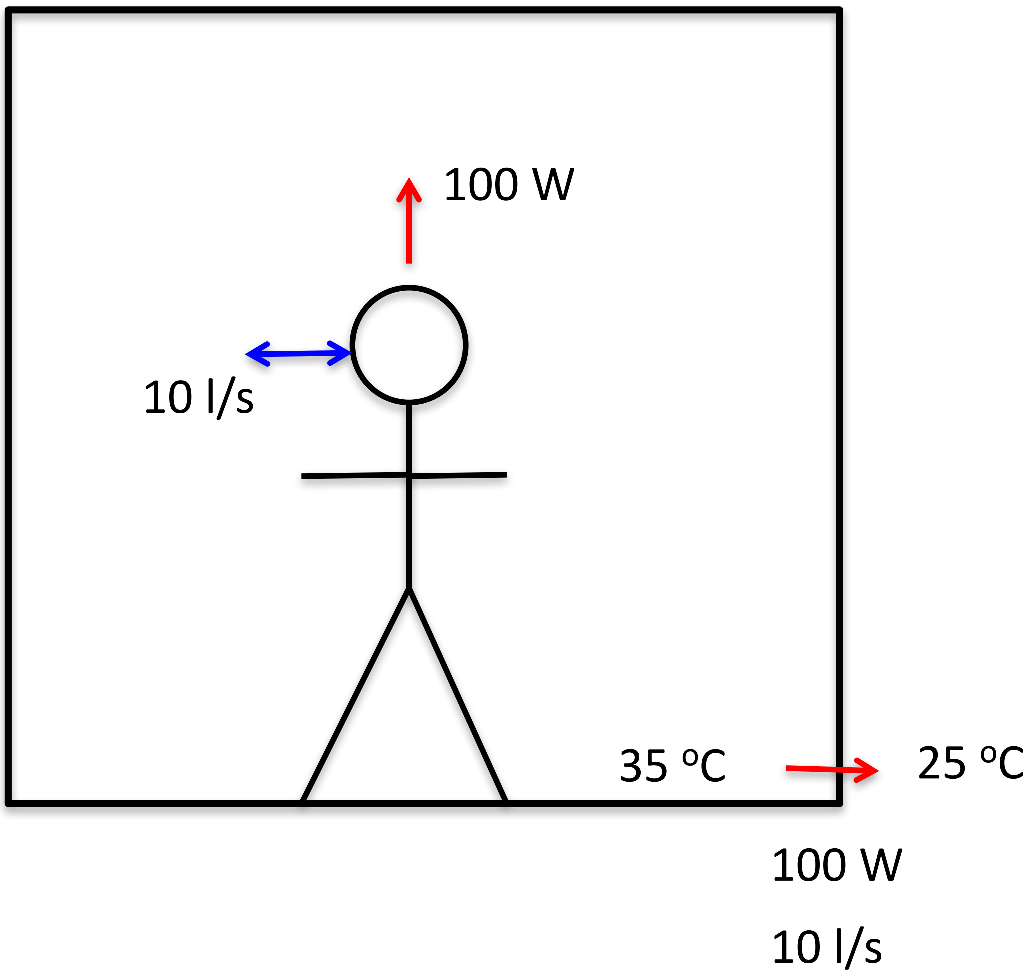
Impacts of climate change

UNIVERSITY OF CAMBRIDGE

Heating



Cooling



UNIVERSITY OF
CAMBRIDGE

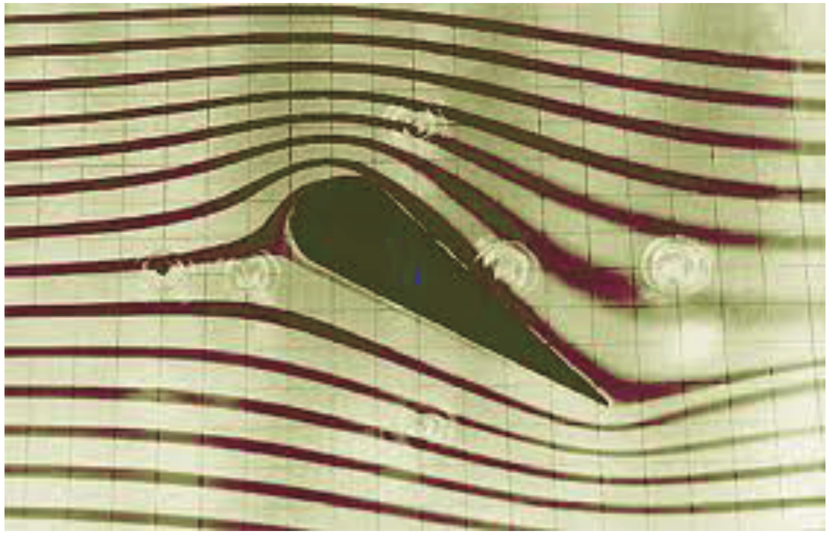
Advanced NV buildings

Queens' Building de Montfort University
Short, Ford & Partners

Green building of the year 1995

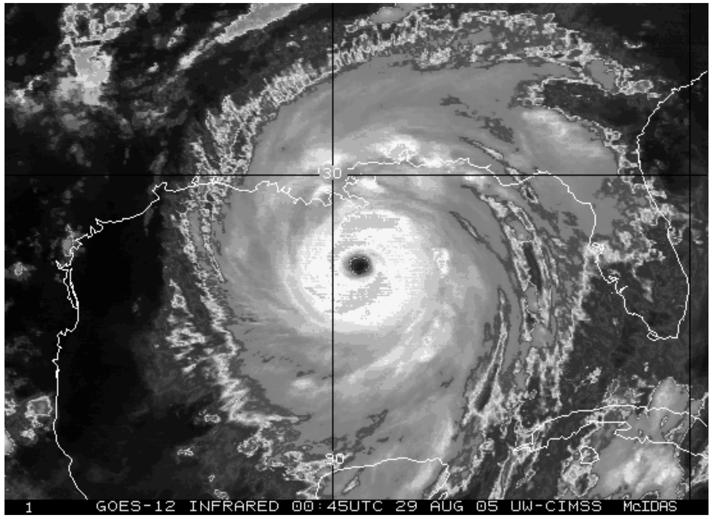
UNIVERSITY OF CAMBRIDGE

Fluid mechanics challenge



Aerospace

boundary conditions



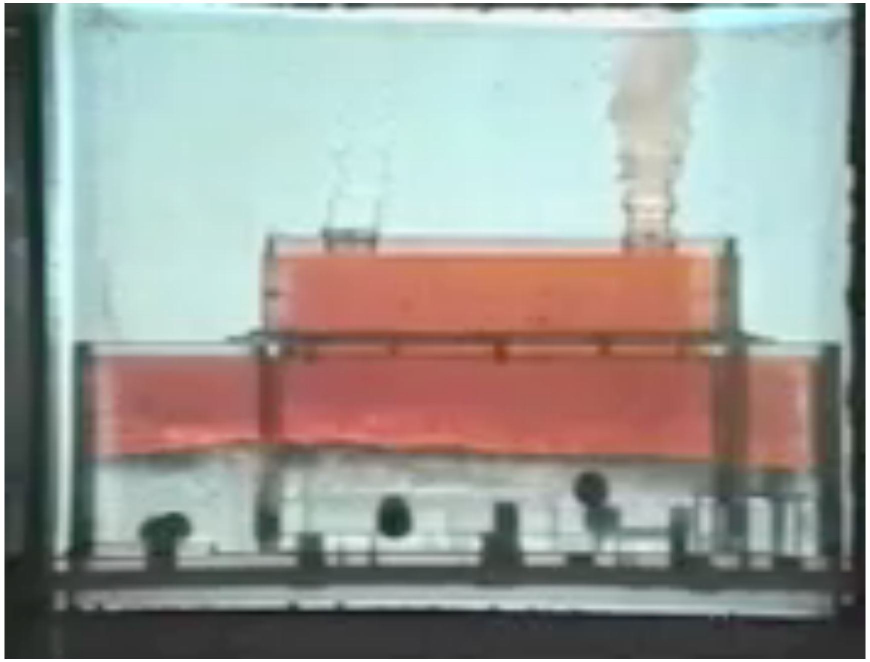
Meteorology

internal dynamics

Currently impossible to compute the full equations without approximation

UNIVERSITY OF CAMBRIDGE

Boundary conditions



UNIVERSITY OF
CAMBRIDGE

Internal dynamics

Plumes – entrain fluid from surroundings

Volume flux increases with height

Temperature decreases with height

UNIVERSITY OF CAMBRIDGE

Modelling options

- Simplified models
  - Network models
  - Integral models
- RANS
  - Turbulence closure
- LES
  - Adaptive grids
  - Turbulence closure
- DNS

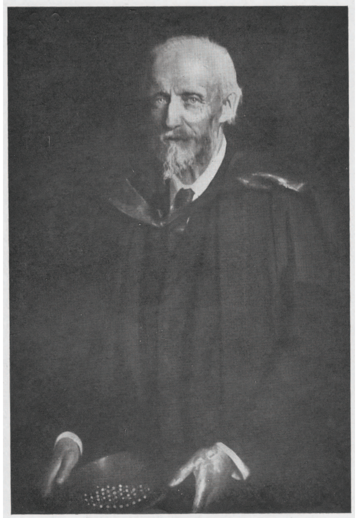
Modelling options

- Simplified models
  - Network models
  - Integral models
- RANS
  - Turbulence closure
- LES
  - Adaptive grids
  - Turbulence closure
- DNS

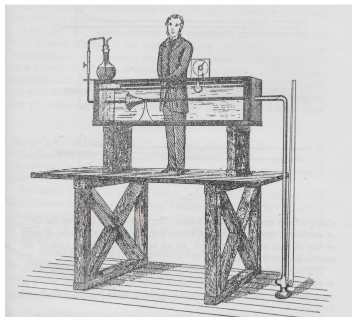
Modelling a building in the lab

Dynamic similarity

When a flow occurs on a smaller scale the effects of friction become disproportionally larger. The challenge for the experimentalist is to ensure that the balance between inertia and friction remain the same as the scale is reduced



OSBORNE REYNOLDS
from a Portrait by John Collier



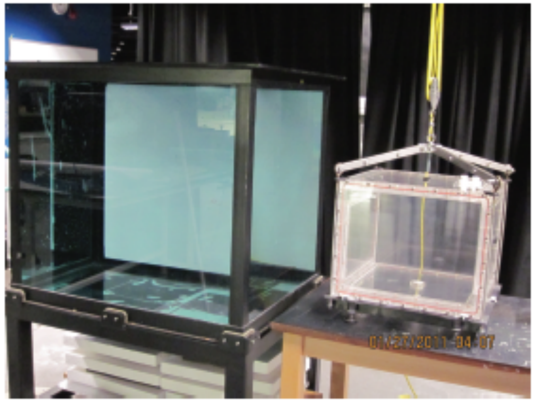
Inertia – friction balance is measured by the Reynolds number

$$Re = \frac{UL}{\nu}$$

U is a typical velocity scale
L is a typical length scale
ν is the kinematic viscosity of the fluid (friction per unit mass)

Full to lab scale

$$Re \sim \frac{\sqrt{g\frac{\Delta\rho}{\rho}}L^{3/2}}{\nu}$$



In a typical model $L_{lab} \sim \frac{1}{20} L_{build}$ so unless we change the properties of the fluid $\Rightarrow$

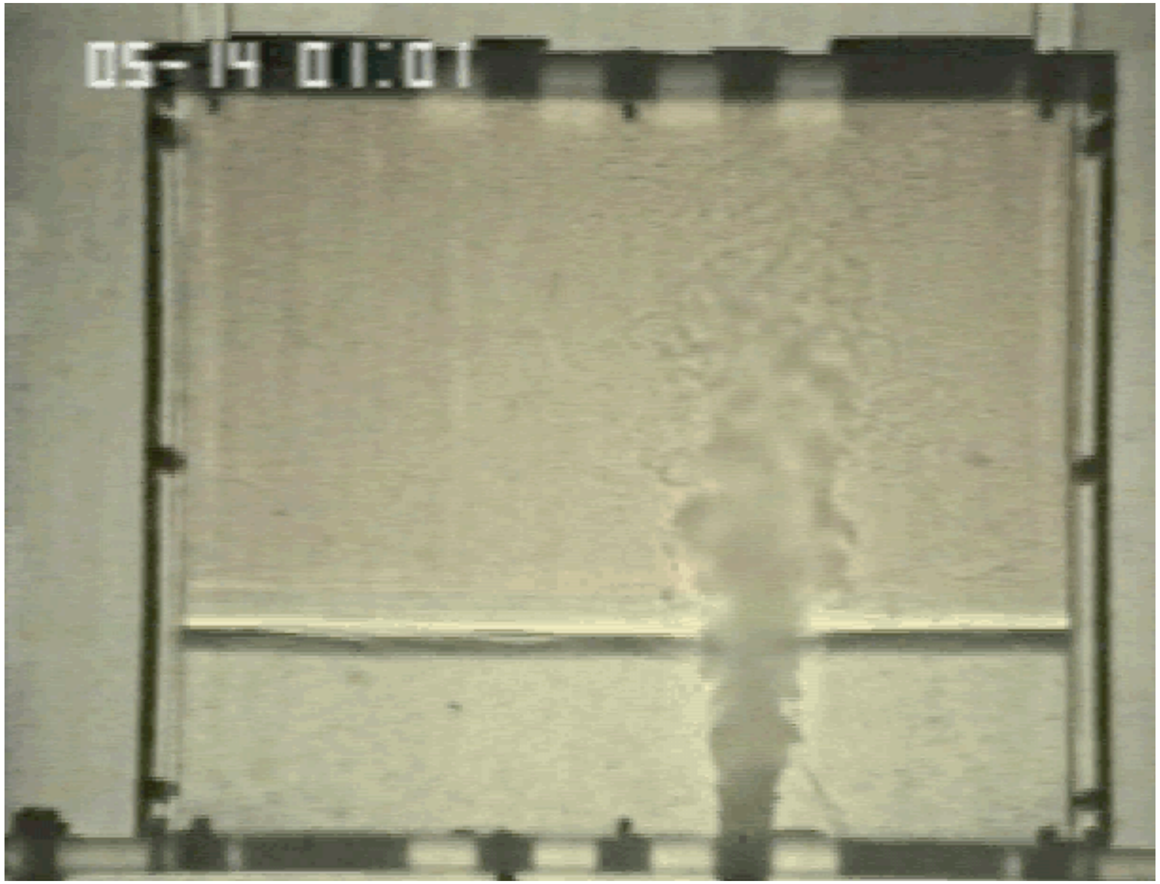
$$Re_{lab} \sim \frac{1}{100} Re_{build}$$

- Work with water – $\nu_{water} \approx \frac{1}{10}\nu_{air}$ – less friction
- Provide buoyancy with salt rather than heat – since $\Delta T \sim$ 10K and $T \sim$ 300K, $\frac{\Delta\rho}{\rho} \equiv \frac{\Delta T}{T} \sim \frac{1}{30}$
  Using salt $\frac{\Delta\rho}{\rho} \sim \frac{1}{10}$ – faster flow
- So we recover a factor of 30 and $Re \sim 300,000$ and friction remains small

UNIVERSITY OF CAMBRIDGE

Displacement ventilation

Single plume

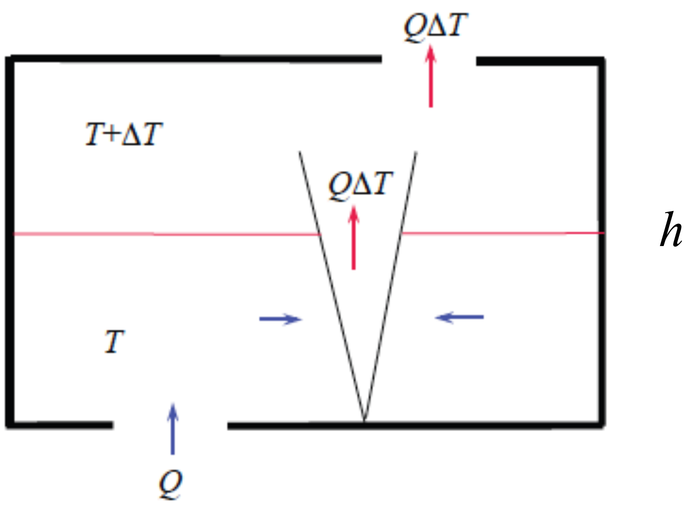


Steady state consists of two uniform layers of different temperatures

UNIVERSITY OF CAMBRIDGE

Displacement ventilation

Single plume



- Upper layer has uniform temperature equal to the temperature of the plume at the interface
- Ventilation flow rate is the volume flux in the plume at the interface

Plume

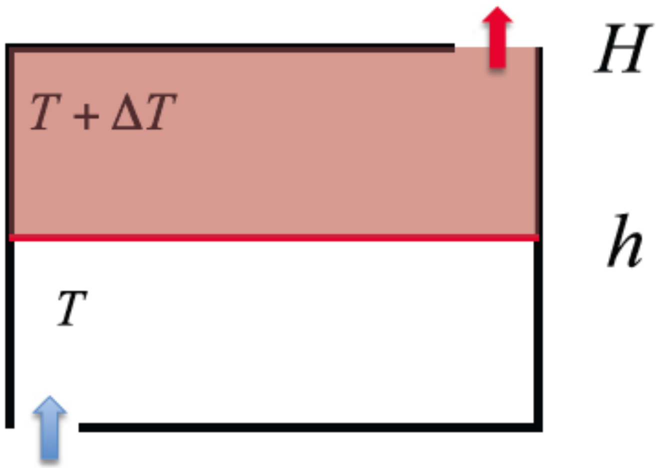
At interface at height h the flow rate Q and the excess temperature ΔT of the plume are related to the heat flux $\mathcal{H}$ by

$$Q \sim \mathcal{H}^{1/3} h^{5/3}$$

$$\Delta T \sim \mathcal{H}^{2/3} h^{-5/3}$$

UNIVERSITY OF CAMBRIDGE

Displacement ventilation



The pressure difference associated with the hot upper layer across the upper opening A_U

$$\Delta p_U = g\frac{\Delta T}{T}(H-h)$$

Across the lower opening A_L the pressure difference is

$$\Delta p_L = g\frac{\Delta T}{T}h$$

These pressure differences drive a ventilation flowrate Q through the two openings

$$\boxed{Q = A^*\sqrt{g\frac{\Delta T}{T}(H-h)}; \quad A^* \equiv \frac{A_L A_U}{\sqrt{A_L^2 + A_U^2}}}$$

UNIVERSITY OF CAMBRIDGE

Displacement ventilation

Local control

$$\boxed{Q = A^* \sqrt{g \frac{\Delta T}{T} (H - h)}; \quad A^* \equiv \frac{A_L A_U}{\sqrt{A_L^2 + A_U^2}}}$$

Upper opening much smaller than the lower opening: $A_U << A_L$

$$A^* \equiv \frac{A_L A_U}{\sqrt{A_L^2 + A_U^2}}$$

$$A^* \equiv \frac{A_L A_U}{\sqrt{A_L^2}} \sim A_U$$

Ventilation rate controlled by the size of the smaller opening

Consequences

$$\boxed{\frac{\frac{h}{H}^{5/2}}{\sqrt{1-\frac{h}{H}}} = \frac{A^*}{H^2}}$$

Denominator gets very small as the interface nears the ceiling $h \to H$

UNIVERSITY OF CAMBRIDGE

Advanced NV buildings

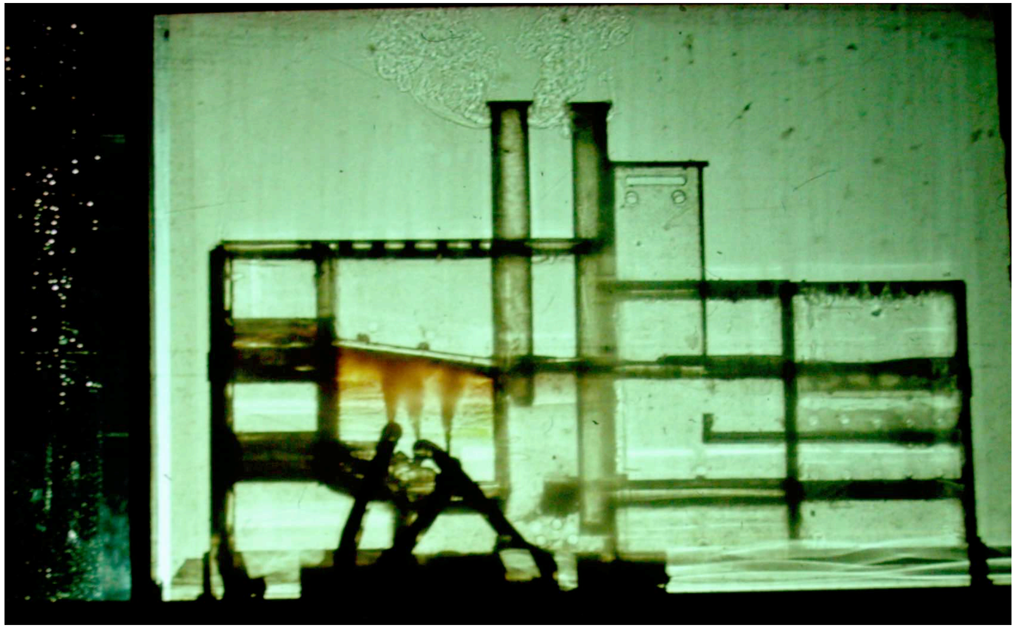
Queens' Building de Montfort University
Short, Ford & Partners

Green building of the year 1995

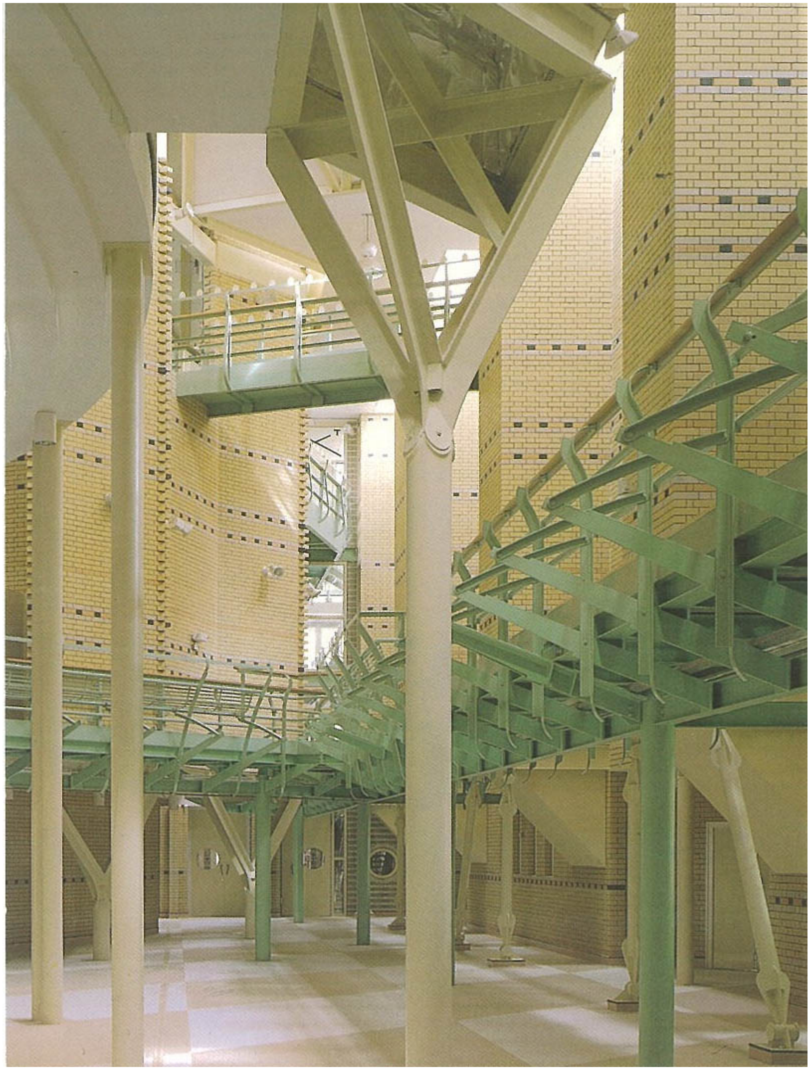
UNIVERSITY OF CAMBRIDGE

Queens' Building de Montfort University

Salt bath model



Interior



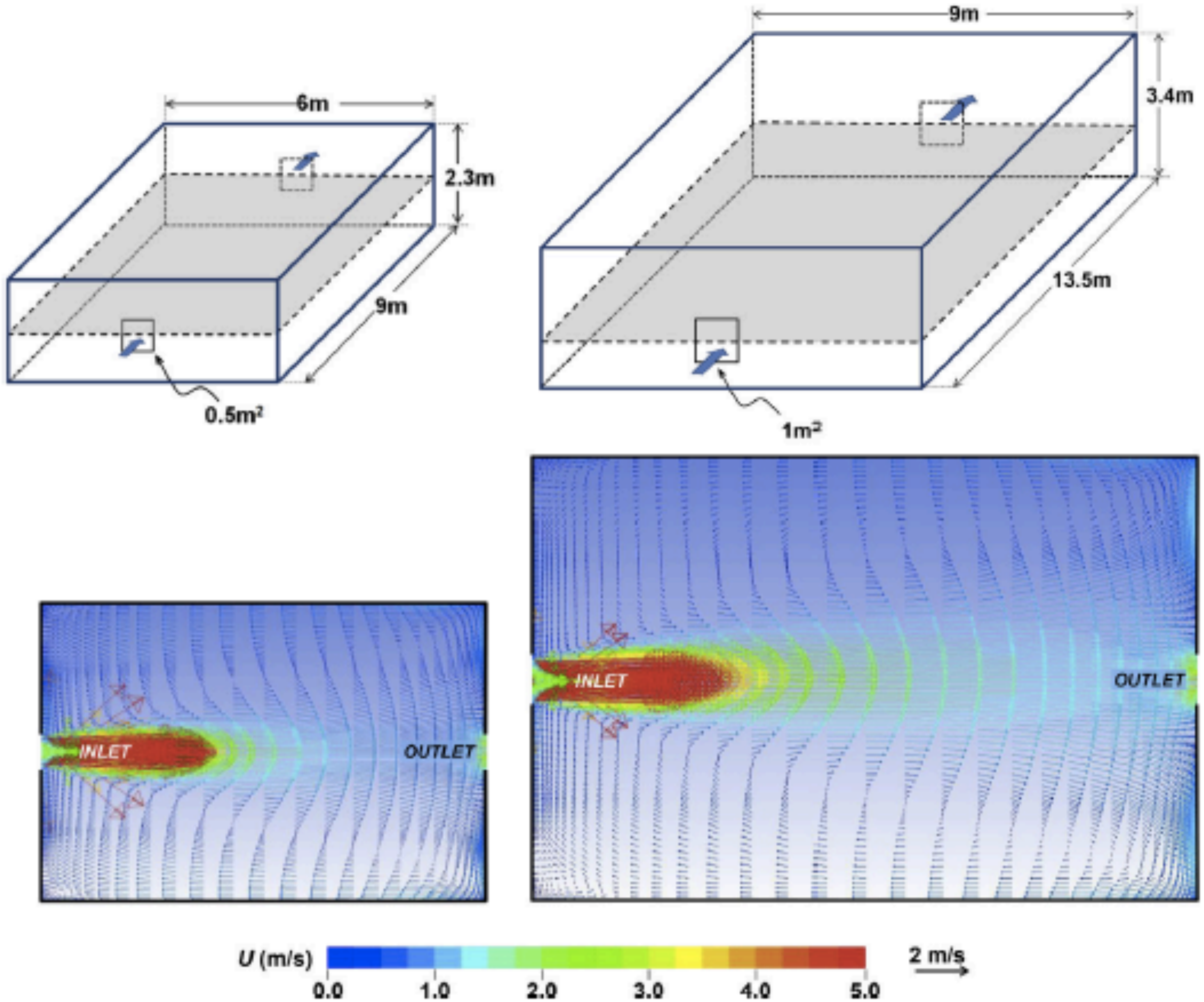
UNIVERSITY OF CAMBRIDGE

Modelling options

- Simplified models
  - Network models
  - Integral models
- RANS
  - Turbulence closure
- LES
  - Adaptive grids
  - Turbulence closure
- DNS

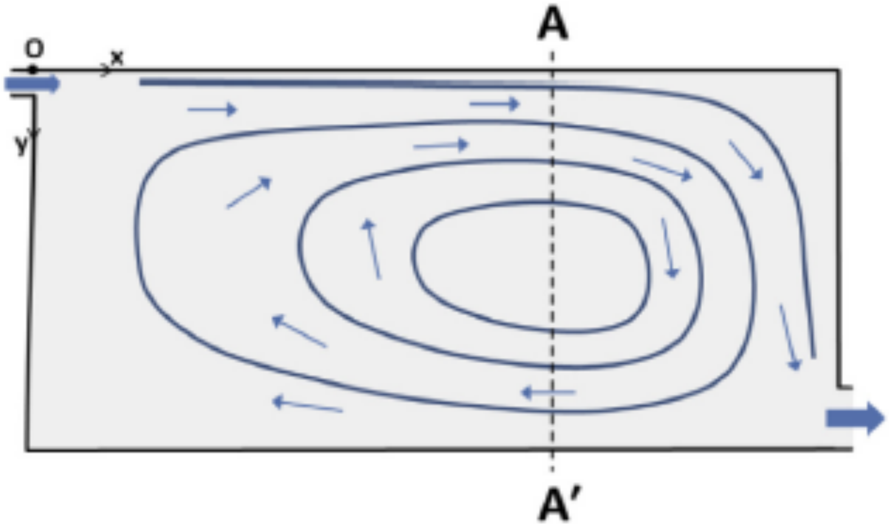
UNIVERSITY OF CAMBRIDGE

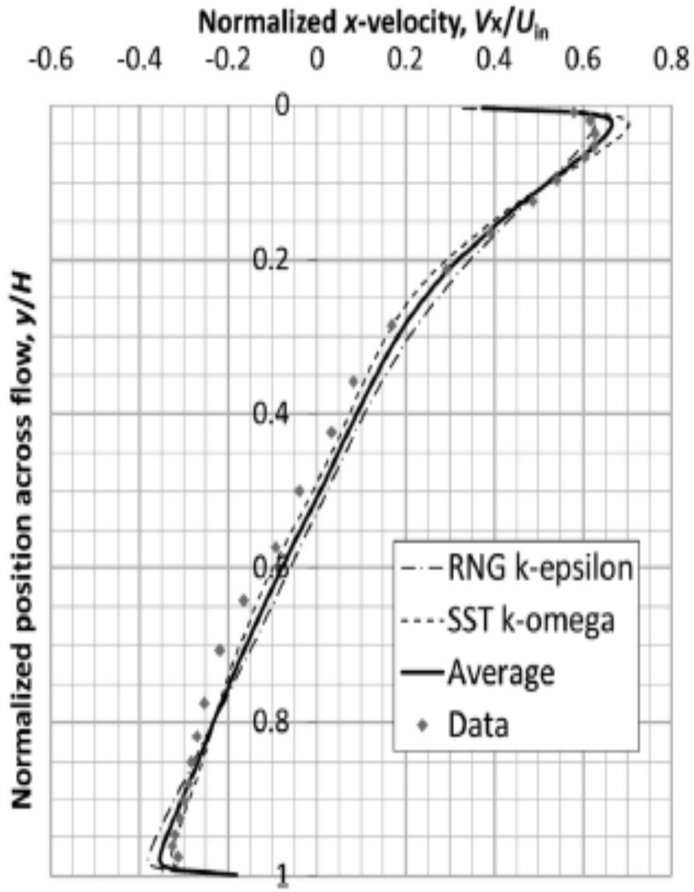
Wind-driven cross ventilation



UNIVERSITY OF CAMBRIDGE

Turbulent closure

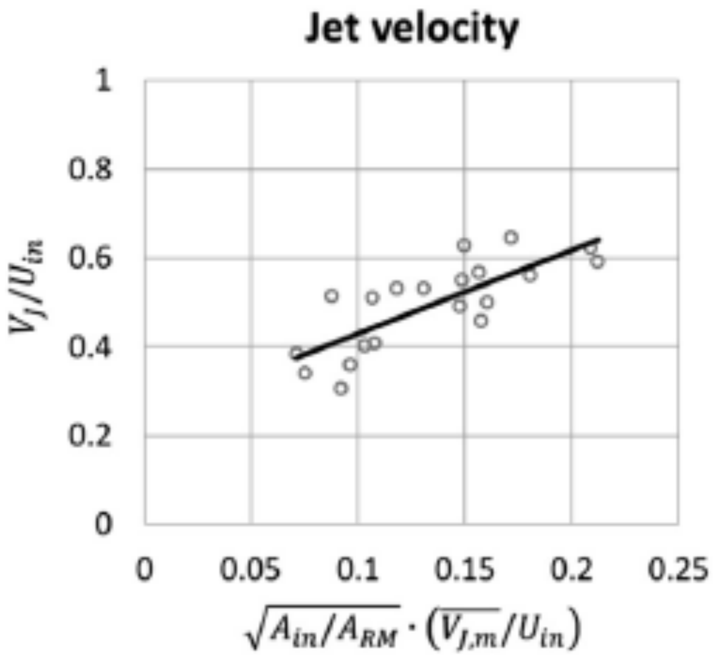


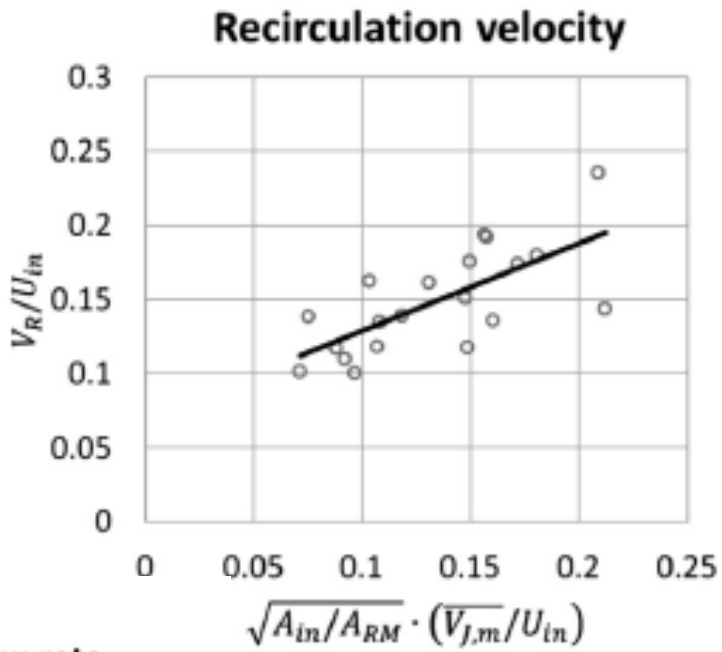


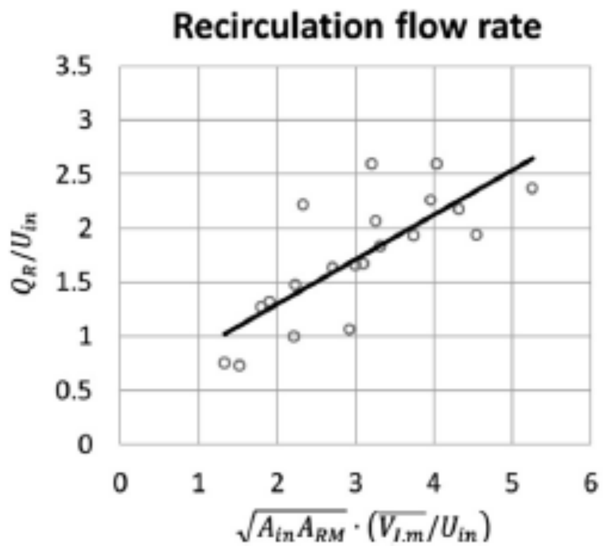
Carrilho da Graca, Daish & PFL 2015
Building and Environ. **89**, 72-85

UNIVERSITY OF CAMBRIDGE

Comparison with zonal model





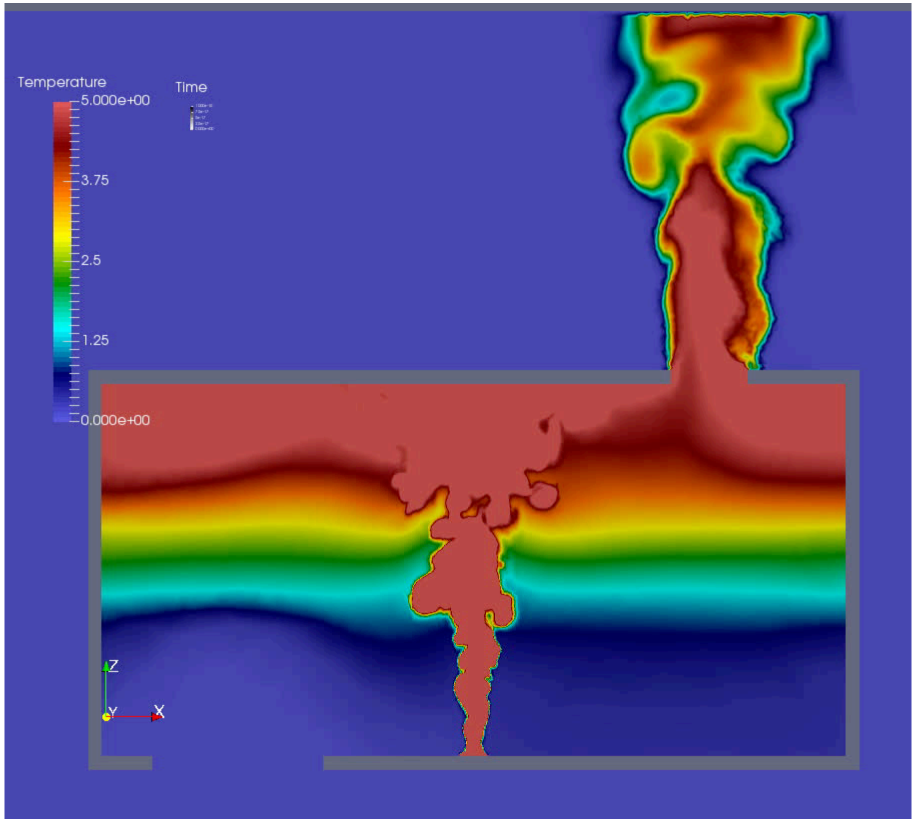


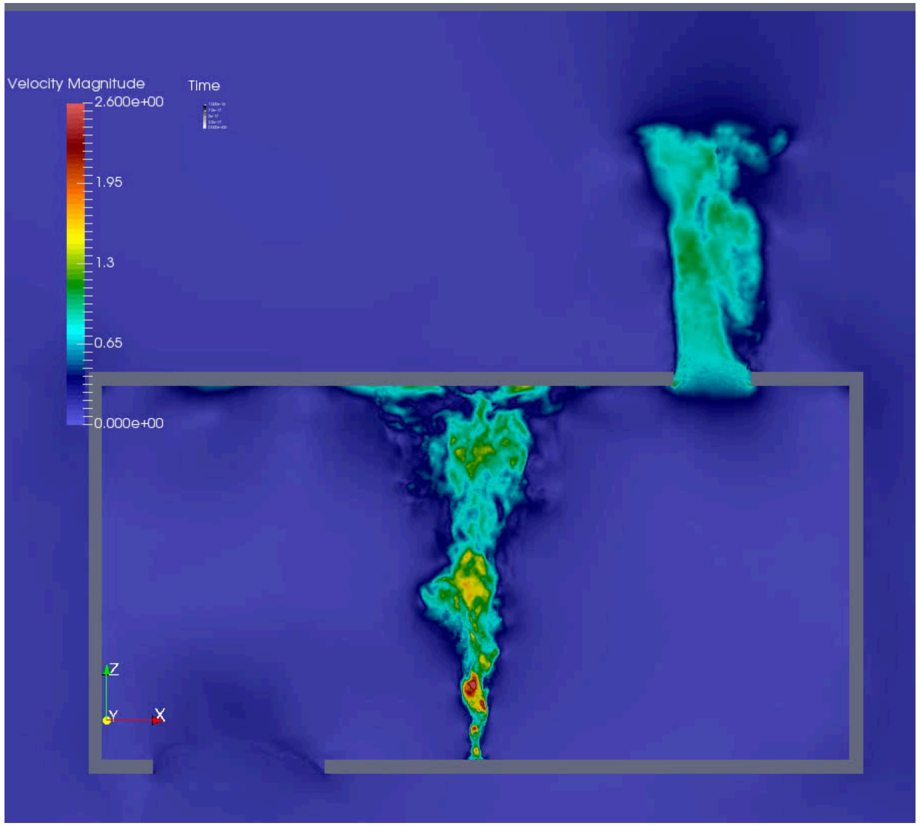
UNIVERSITY OF CAMBRIDGE

Modelling options

- Simplified models
  - Network models
  - Integral models
- RANS
  - Turbulence closure
- LES
  - Adaptive grids
  - Turbulence closure
- DNS

Single plume with displacement ventilation





6 x 6 x 3m room with 1.5kW heater

Hesse, Burridge & Pain 2017

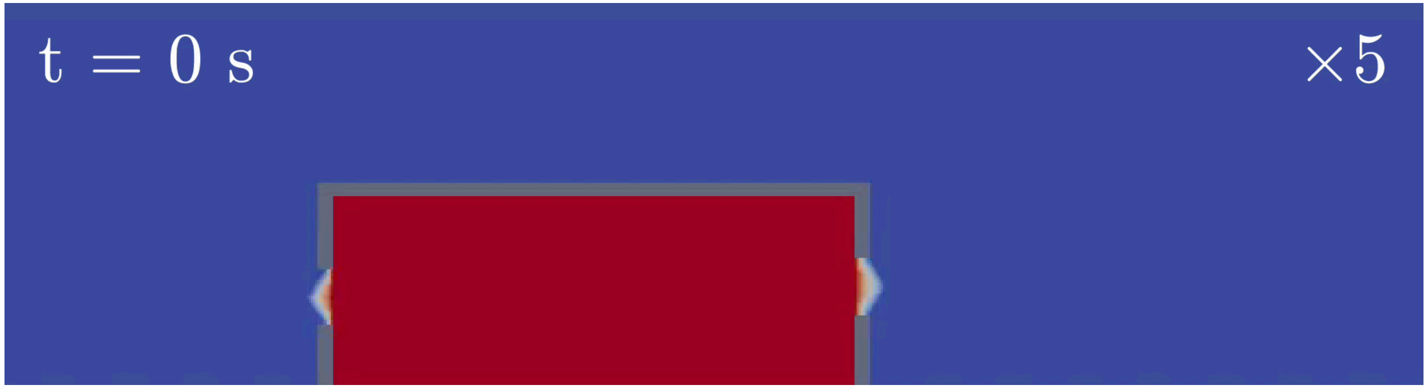
UNIVERSITY OF CAMBRIDGE

Test room

Wind-driven cross ventilation

side view

Air
Full scale

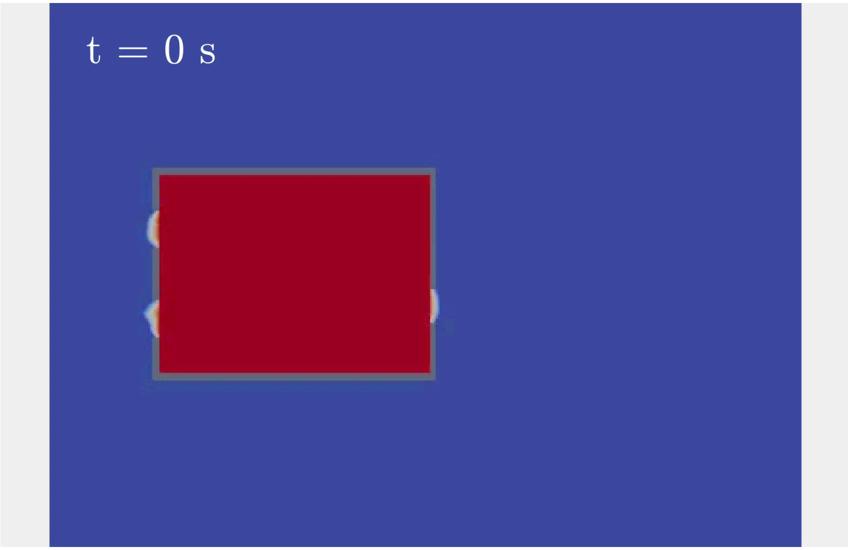


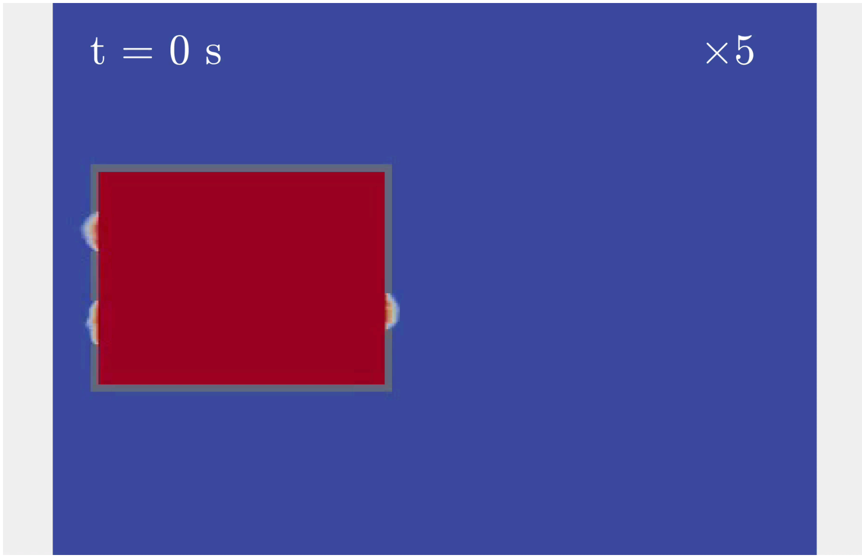
Water
Lab scale

UNIVERSITY OF CAMBRIDGE

Wind-driven cross ventilation

top view





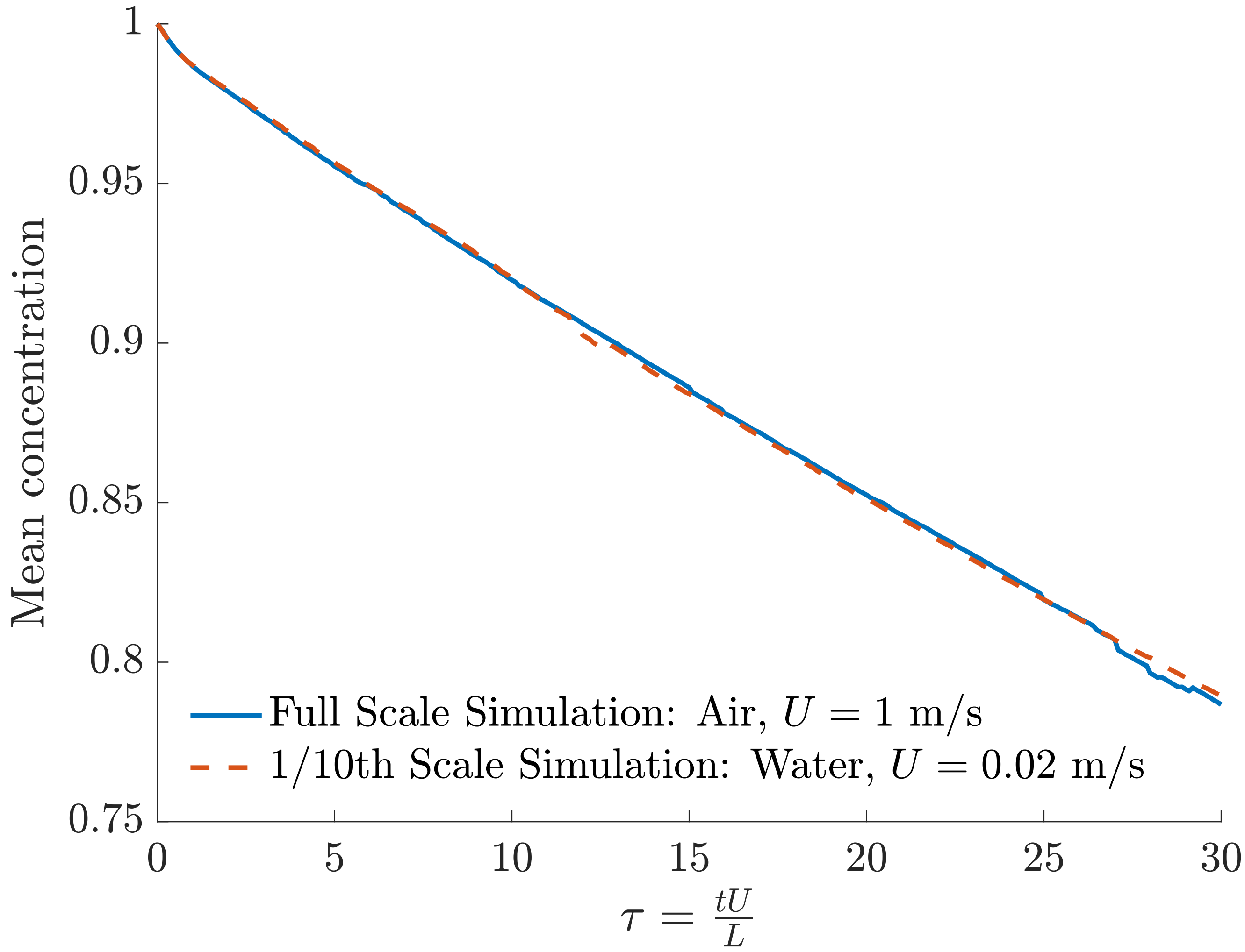
Air
Full scale

Water
Lab scale

Davies Wykes, Debay & PFL 2018

UNIVERSITY OF CAMBRIDGE

Decay of mean concentration

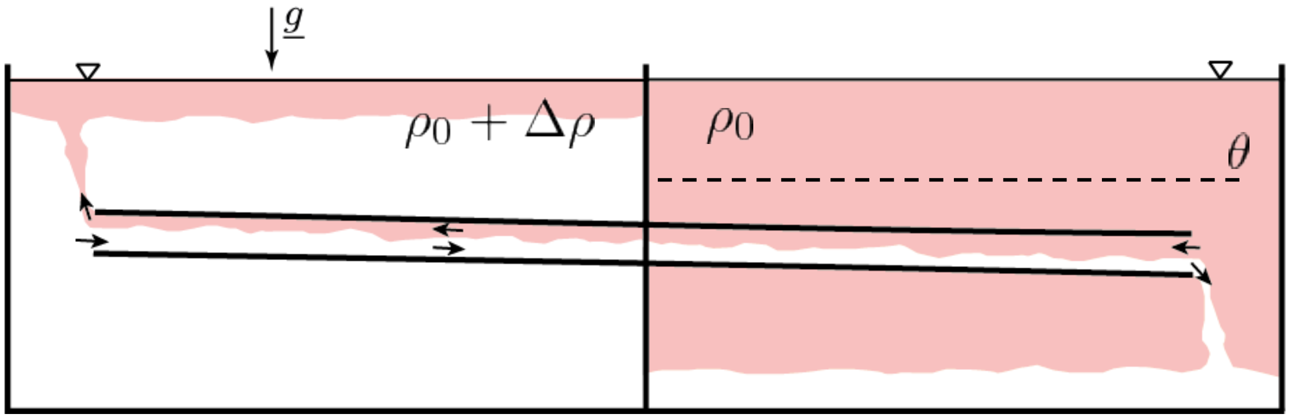


UNIVERSITY OF CAMBRIDGE

Modelling options

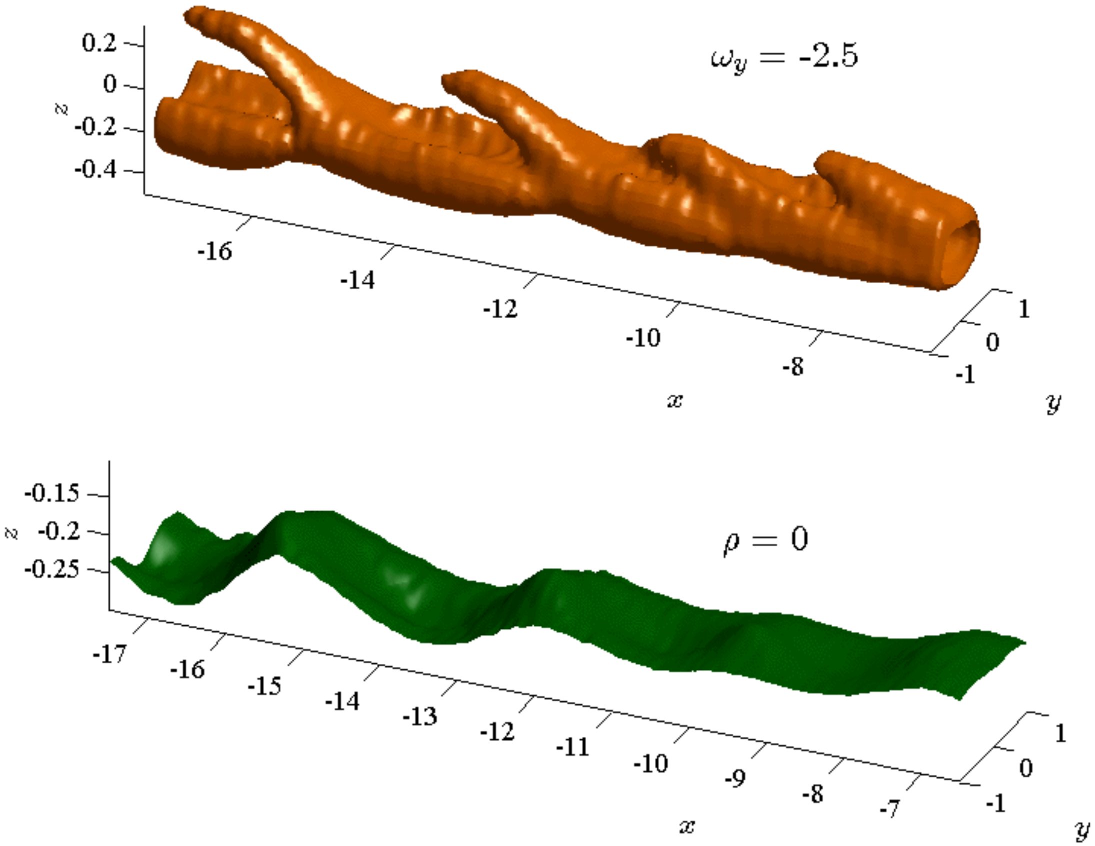
- Simplified models
  - Network models
  - Integral models
- RANS
  - Turbulence closure
- LES
  - Adaptive grids
  - Turbulence closure
- DNS

Inclined duct experiment



- **Exchange flow** between two reservoirs
- Two-layer stratified shear flow with **sustained forcing**
- **Simple configuration** but **rich range of nonlinear behaviours**

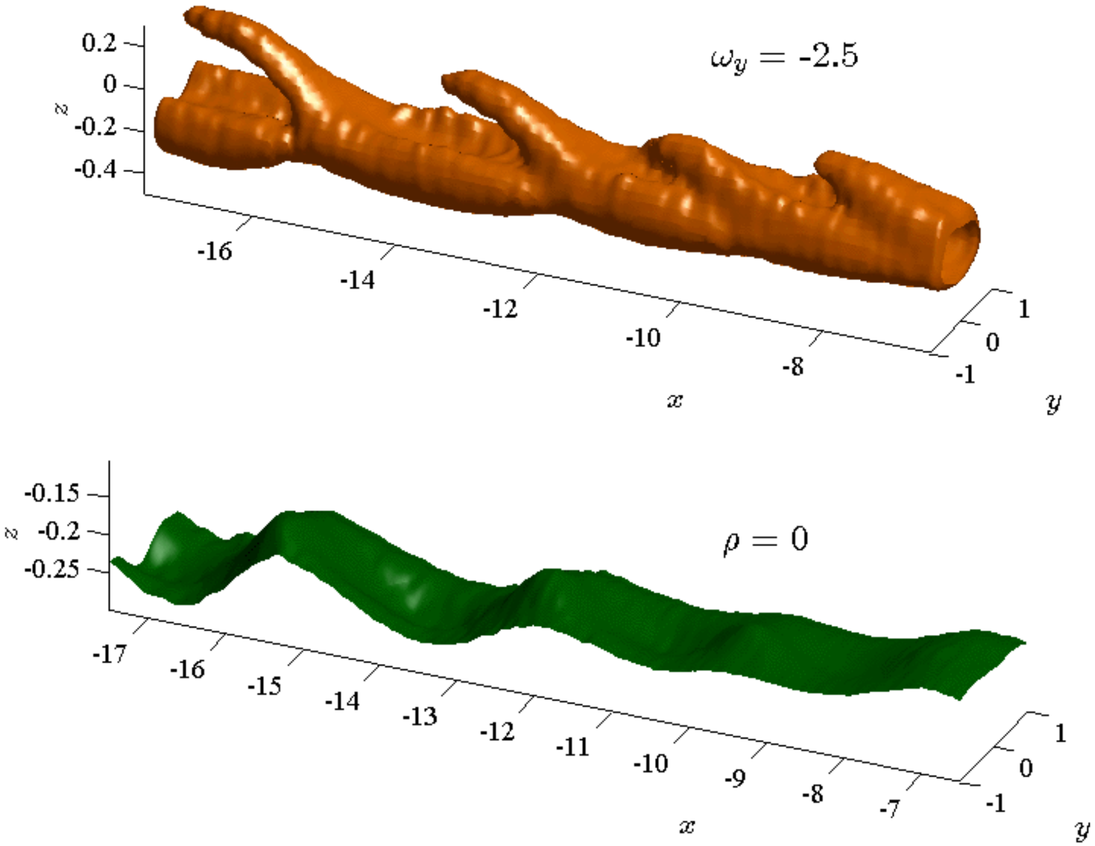
3D structures



Lefauve, Partridge & PFL 2017

UNIVERSITY OF CAMBRIDGE

3D structures



Nessie!

The Loch Ness monster

Lefauve, Partridge & PFL 2018

UNIVERSITY OF CAMBRIDGE

Challenges

- Single-sided ventilation
- People movement
- Connections to urban design

Challenges

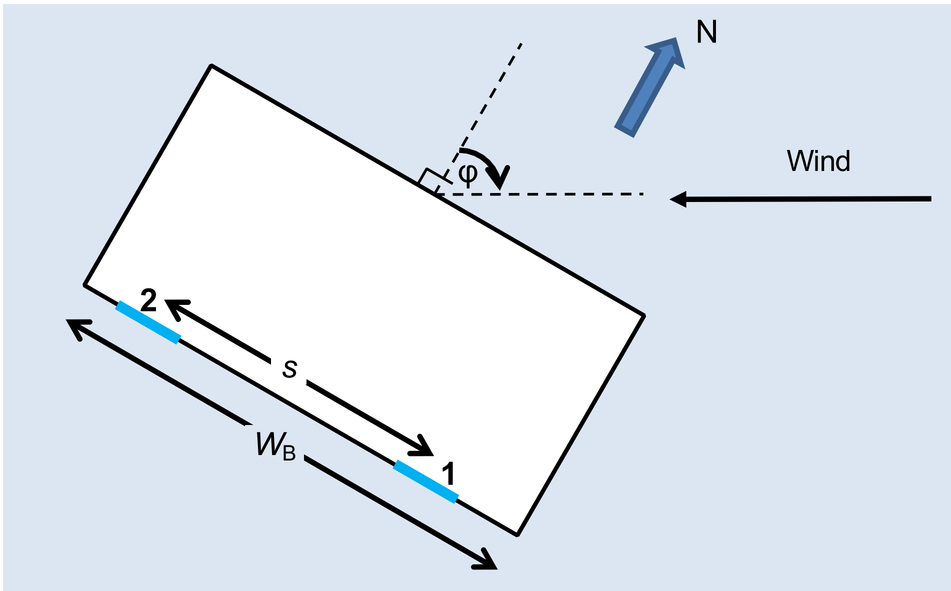
- Single-sided ventilation

- People movement

- Connections to urban design

Single-sided ventilation

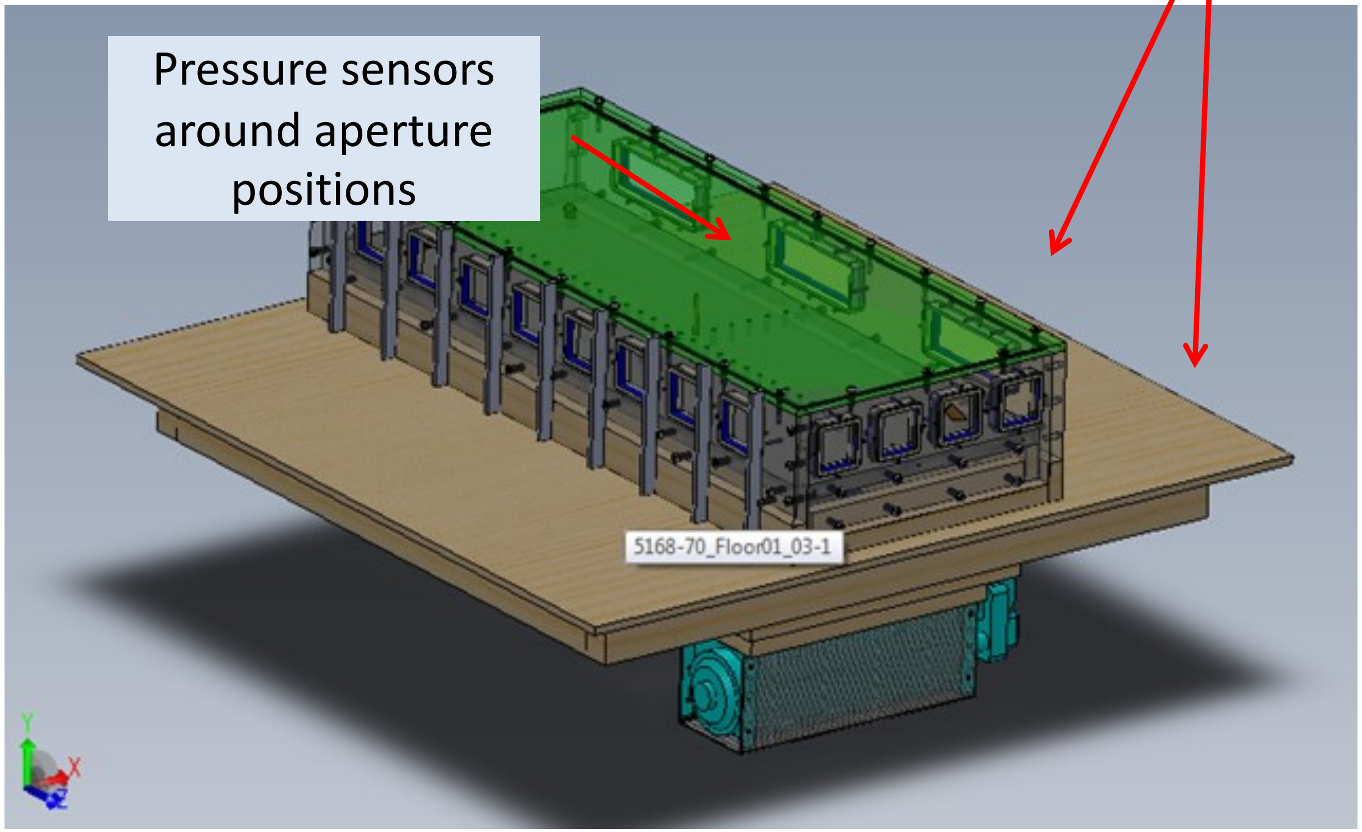
- **Ventilation rate due to 1 or more openings in same façade**
- **Dependence on wind angle and opening size and position**



UNIVERSITY OF CAMBRIDGE

Wind tunnel tests

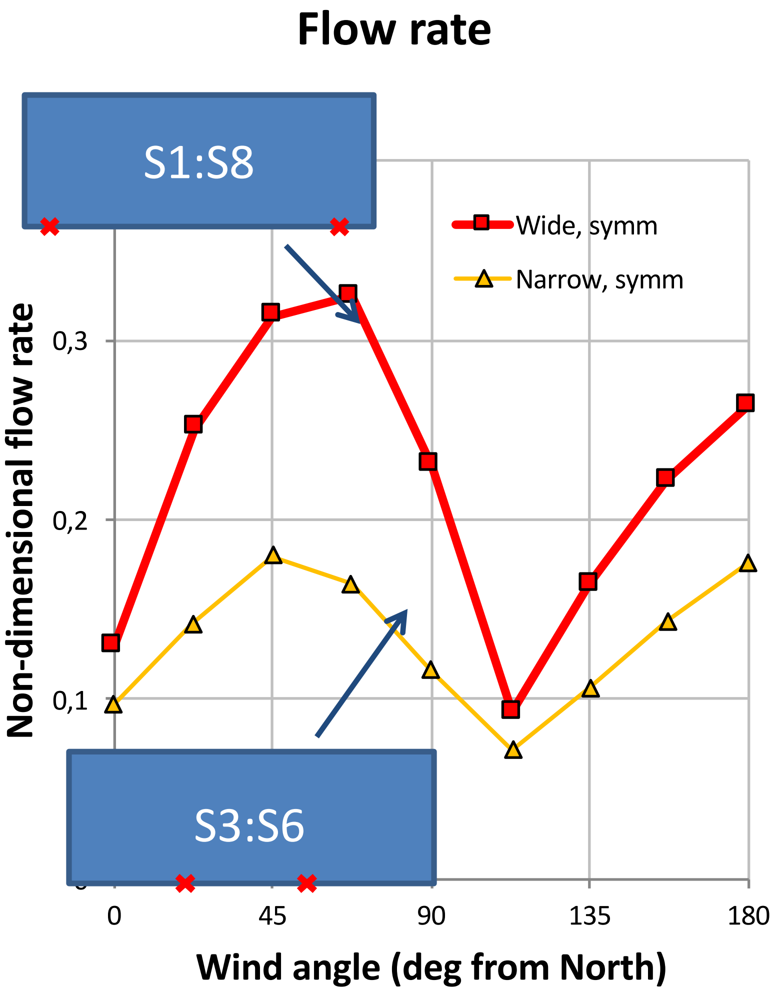
FID (concentration) sensors

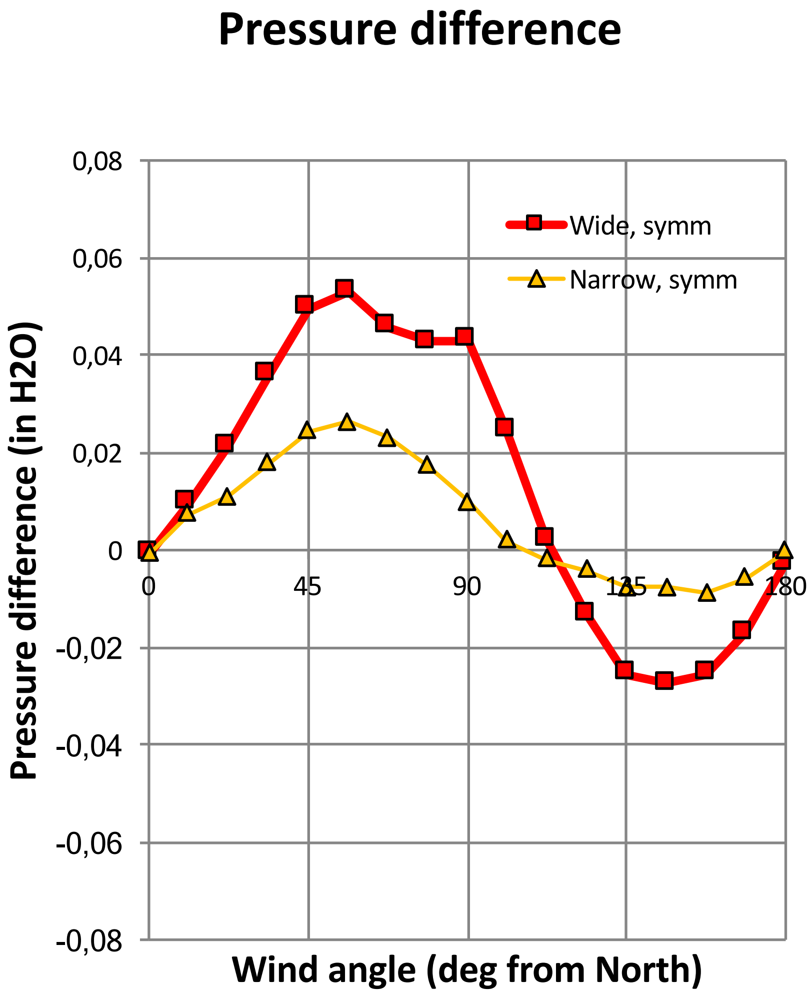


2-story: approx 5:2:1, H = 10cm

UNIVERSITY OF CAMBRIDGE

Flow rate and pressure difference





UNIVERSITY OF CAMBRIDGE

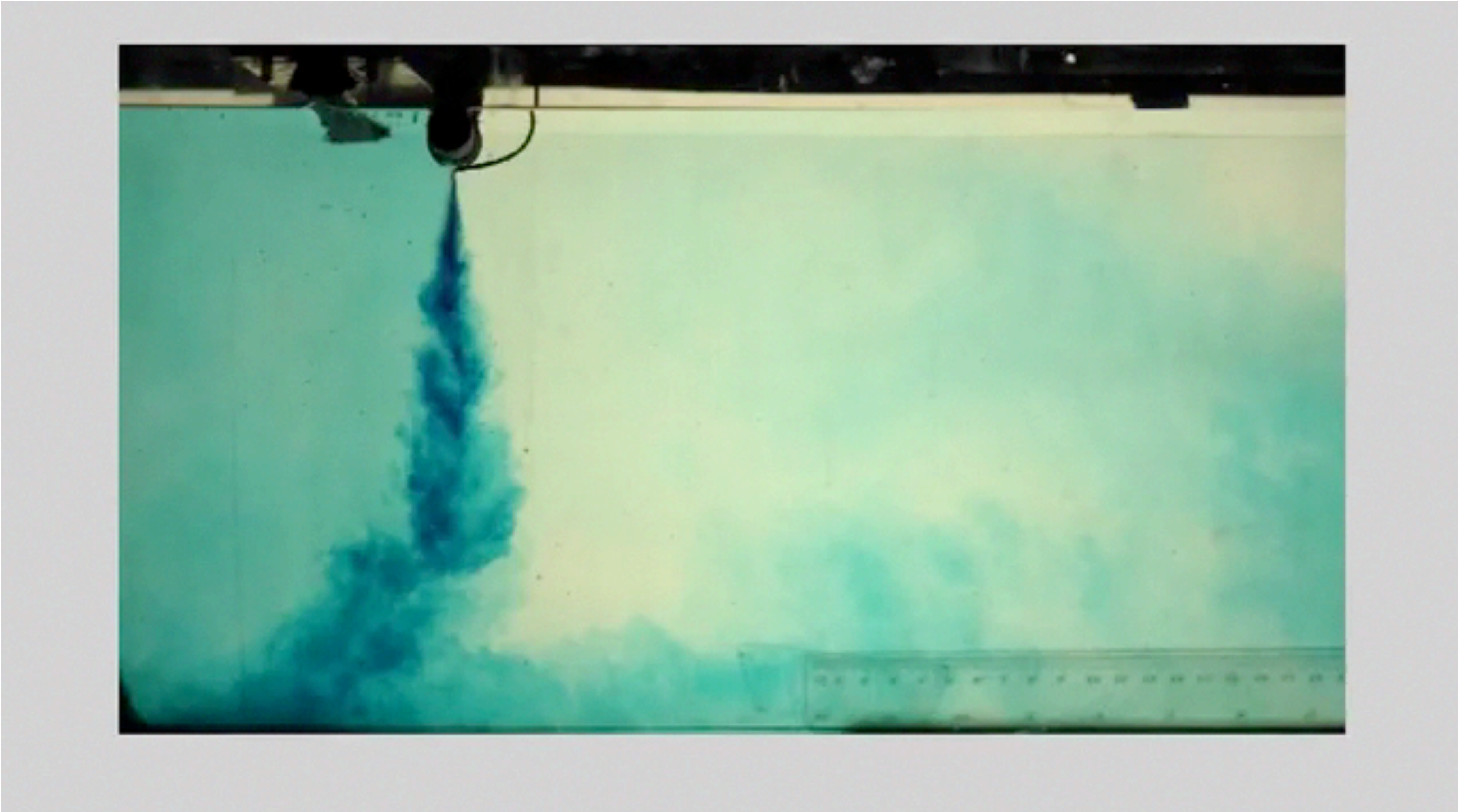
Pumping through openings in the lee

UNIVERSITY OF CAMBRIDGE

Challenges

- Single-sided ventilation
- People movement
- Connections to urban design

Walking through an air curtain



Jha, Frank & Linden 2017

UNIVERSITY OF CAMBRIDGE

Challenges

- Single-sided ventilation
- People movement
- Connections to urban design

MAGIC

Managing Air for Green Inner Cities

The **0-0** Challenge:

Can we develop cities with no air pollution and no heat-island effect by 2050?

About

Imagine a city with no air pollution or heat island…

- Current HVAC system is carbon intensive

We need to think differently…

- Natural ventilation in buildings
- Diluted air pollution levels
- Increased albedo
- Integrated green and blue spaces
- Public education and policy change

MAGIC Fluid mechanics

Fluidity: Large Eddy Simulations with an adaptive mesh

Wind tunnel: study of test site 300m radius at 1:200 scale

Water flume: modelling indoor-outdoor exchange

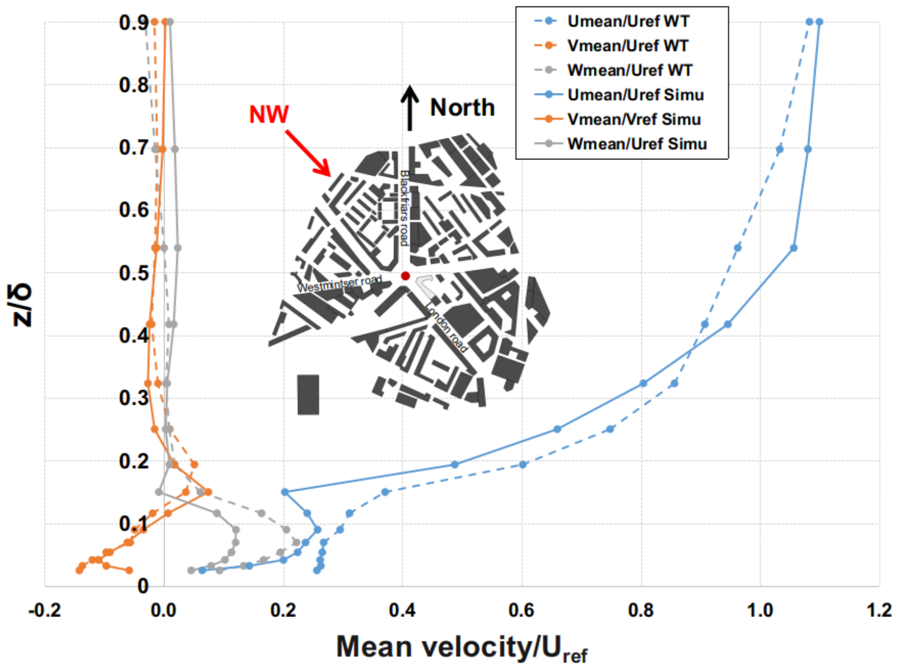
Monitoring: indoor and outdoor monitoring of test site

Test Site

Borough of Southwark

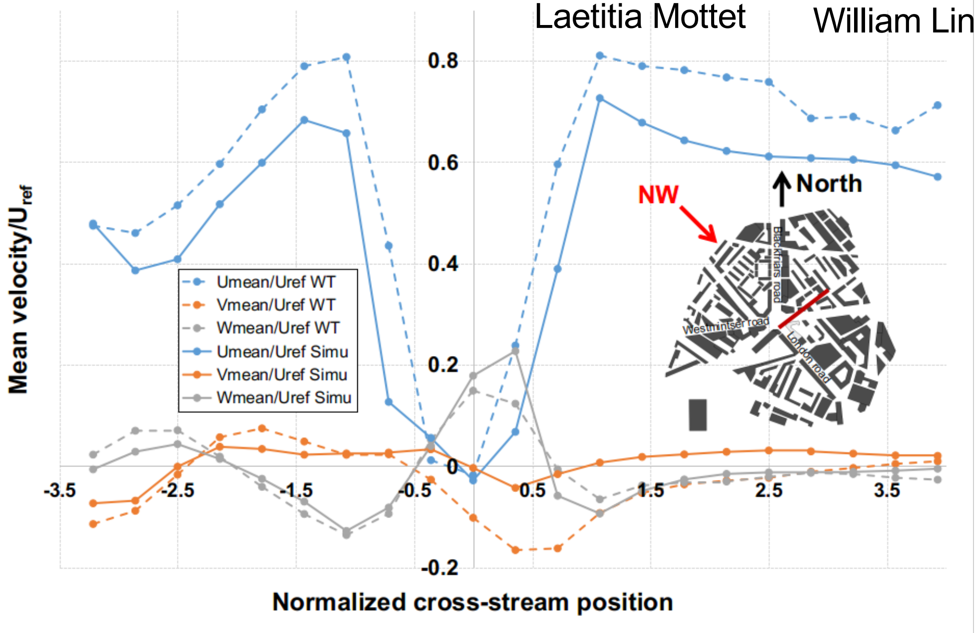
Neighboorhood scale simulations

Comparison with wind tunnel experiment



Laetitia Mottet

William Lin



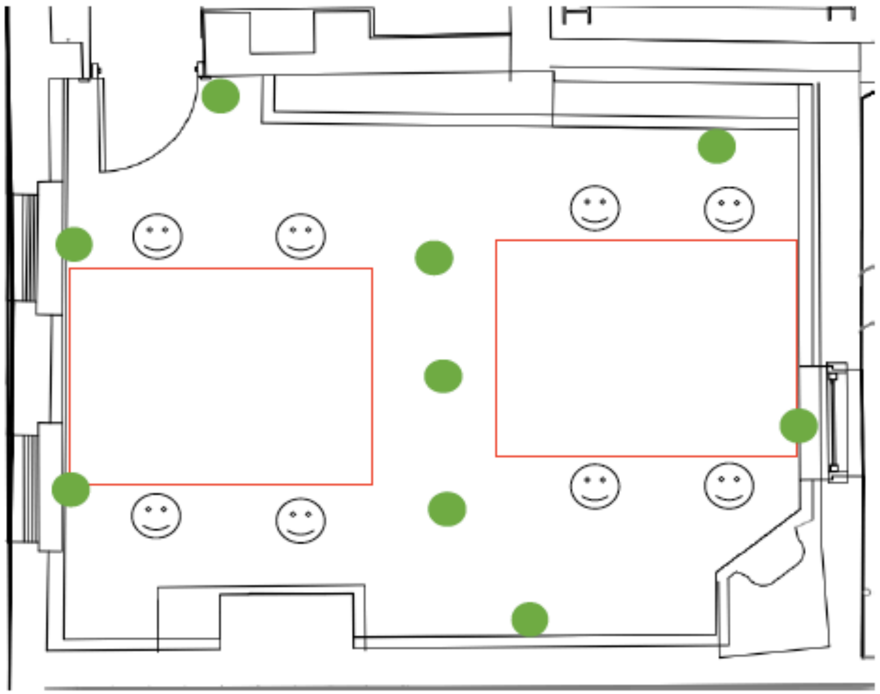
UNIVERSITY OF CAMBRIDGE

Sensor network

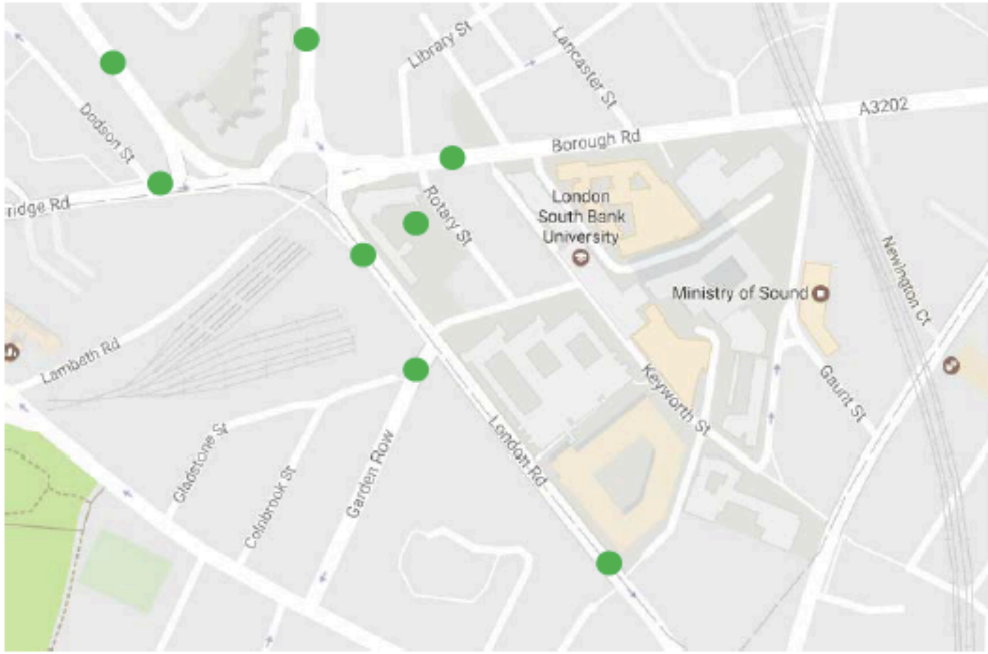
Sensor Network

MAGIC

Envisaging a world with greener cities



Indoor Sensor Network

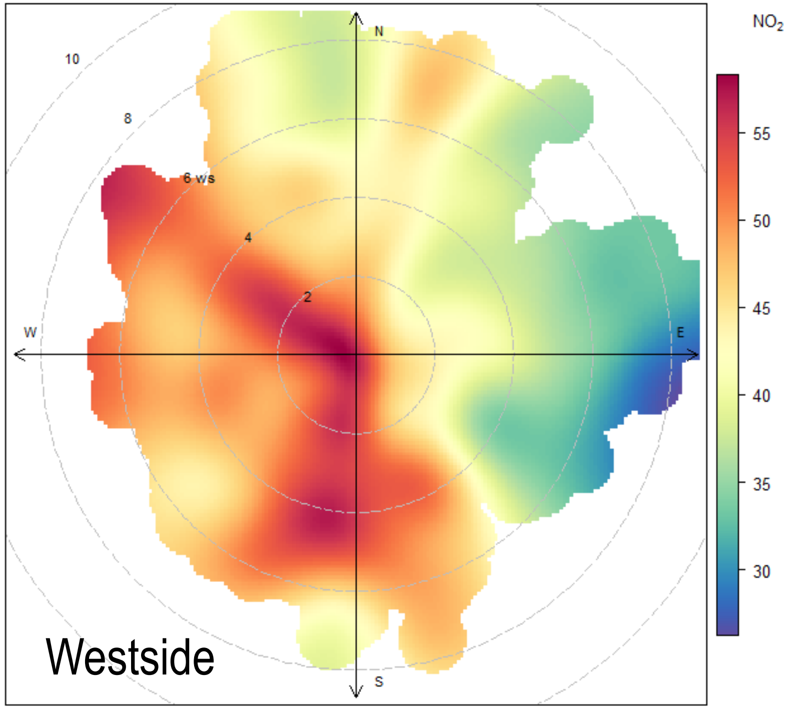


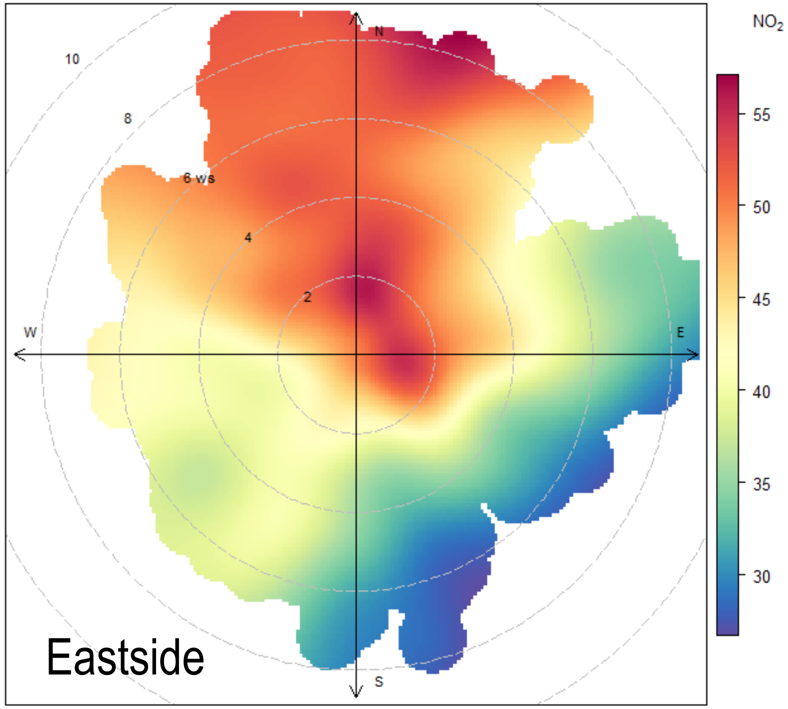
Outdoor Sensor Network (Street, City)

- High temporal resolution and high spatial resolution

UNIVERSITY OF CAMBRIDGE

Outdoor NO_2 on London Road

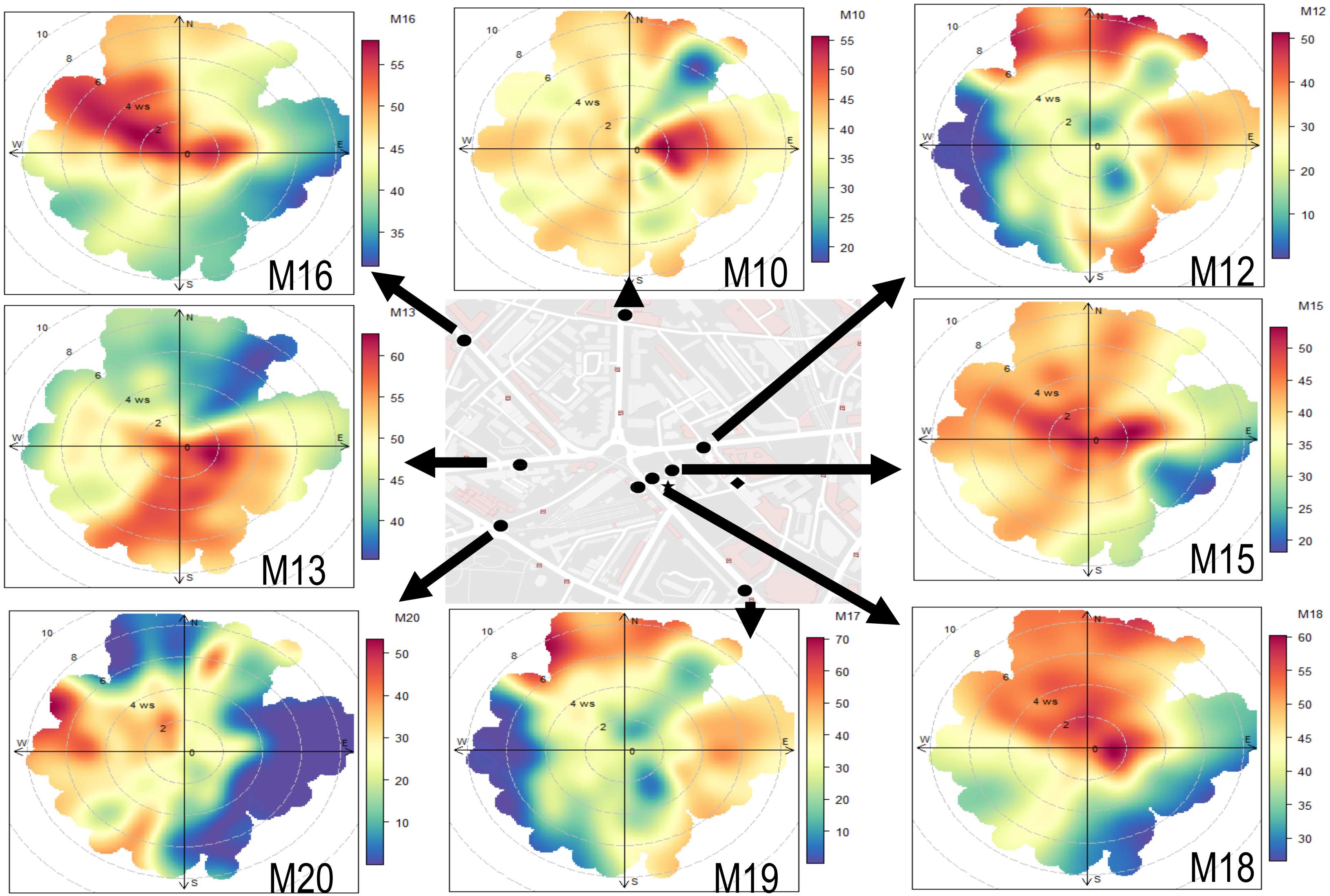




- Street Canyon effect results in a higher concentration on westside road and a lower concentration on the eastside road
- Statistical plots for comparison with models

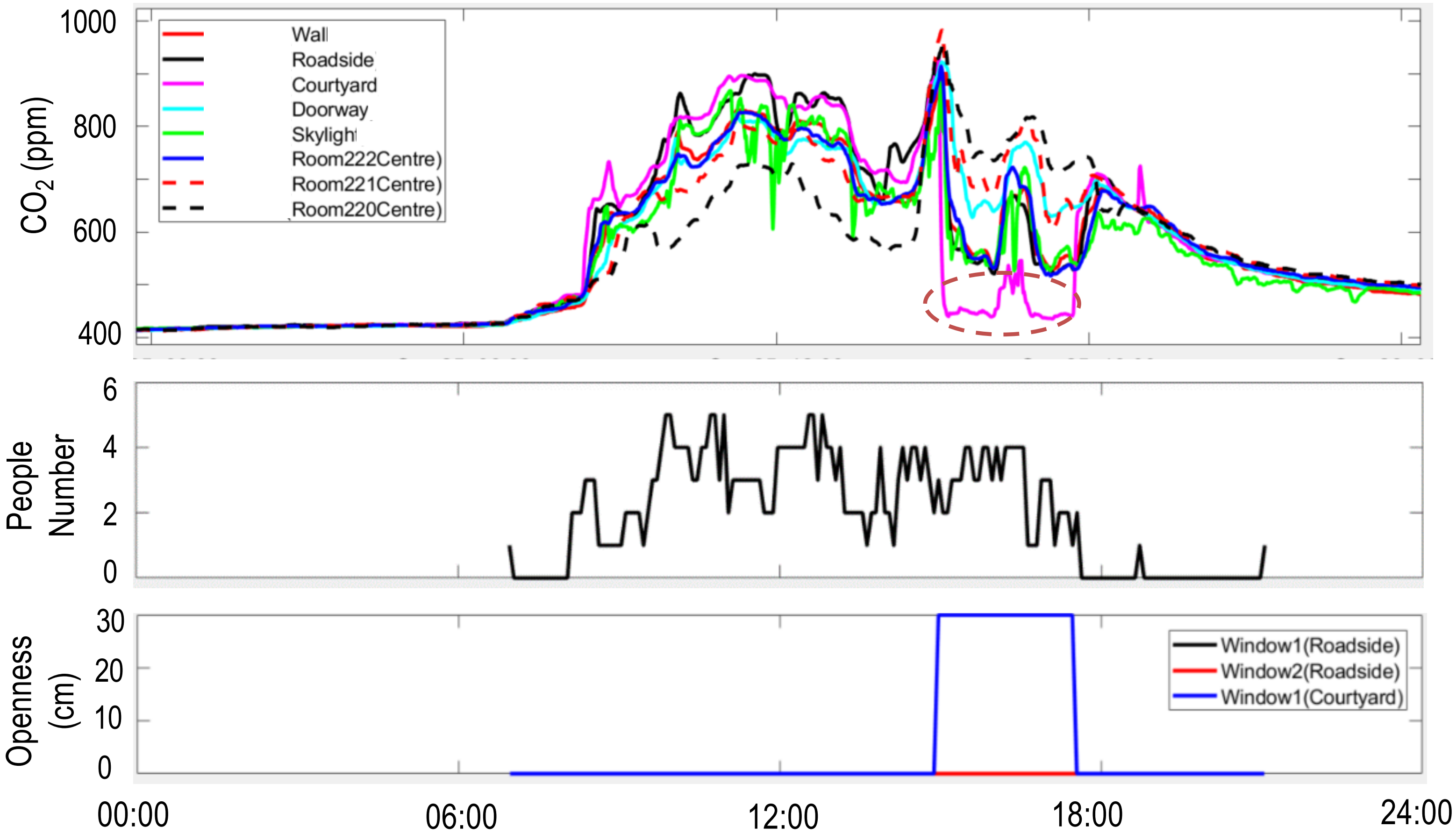
UNIVERSITY OF CAMBRIDGE

Outdoor monitoring



UNIVERSITY OF
CAMBRIDGE

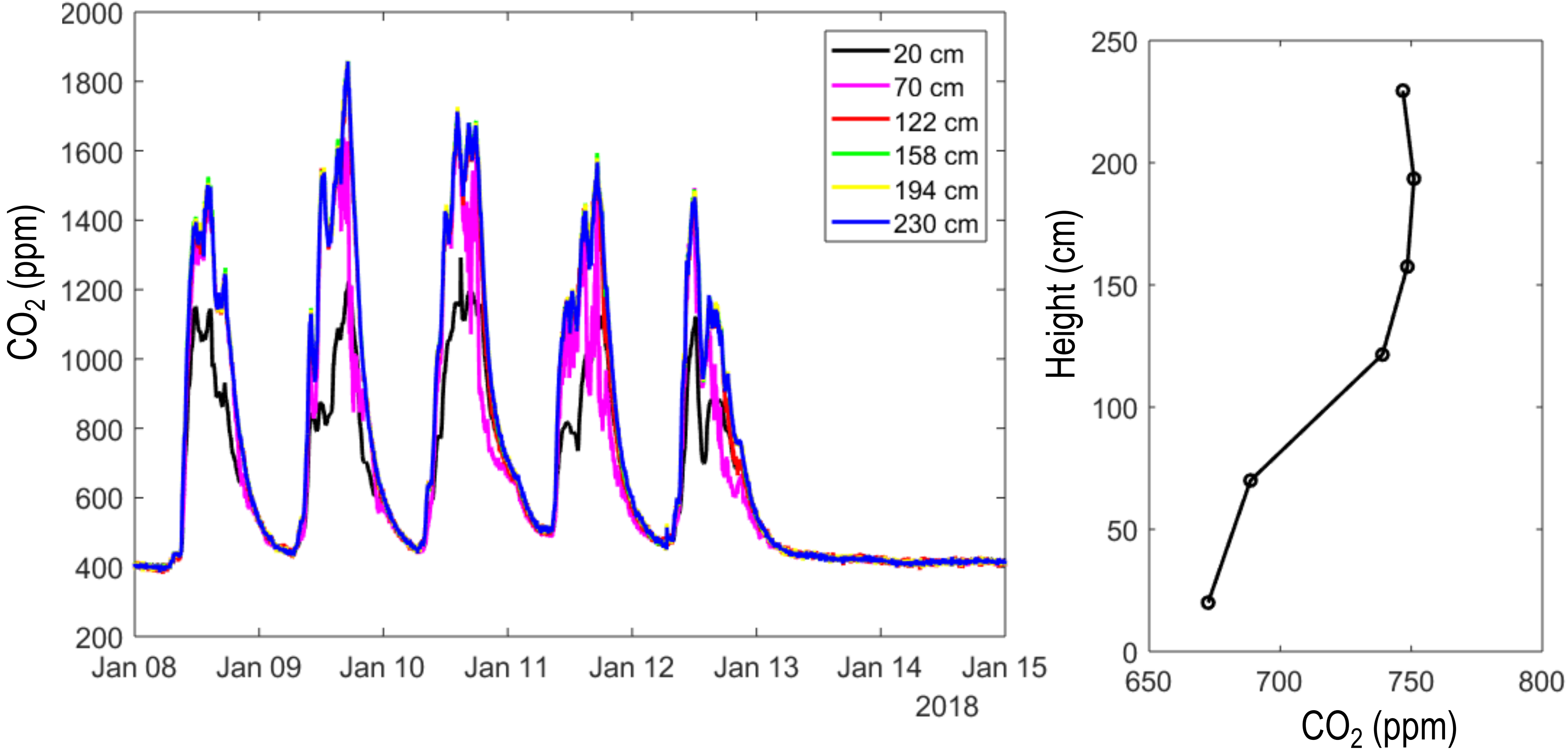
Indoor CO_2 – Single-sided Ventilation



- 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

UNIVERSITY OF CAMBRIDGE

Indoor CO_2 Vertical Stratification



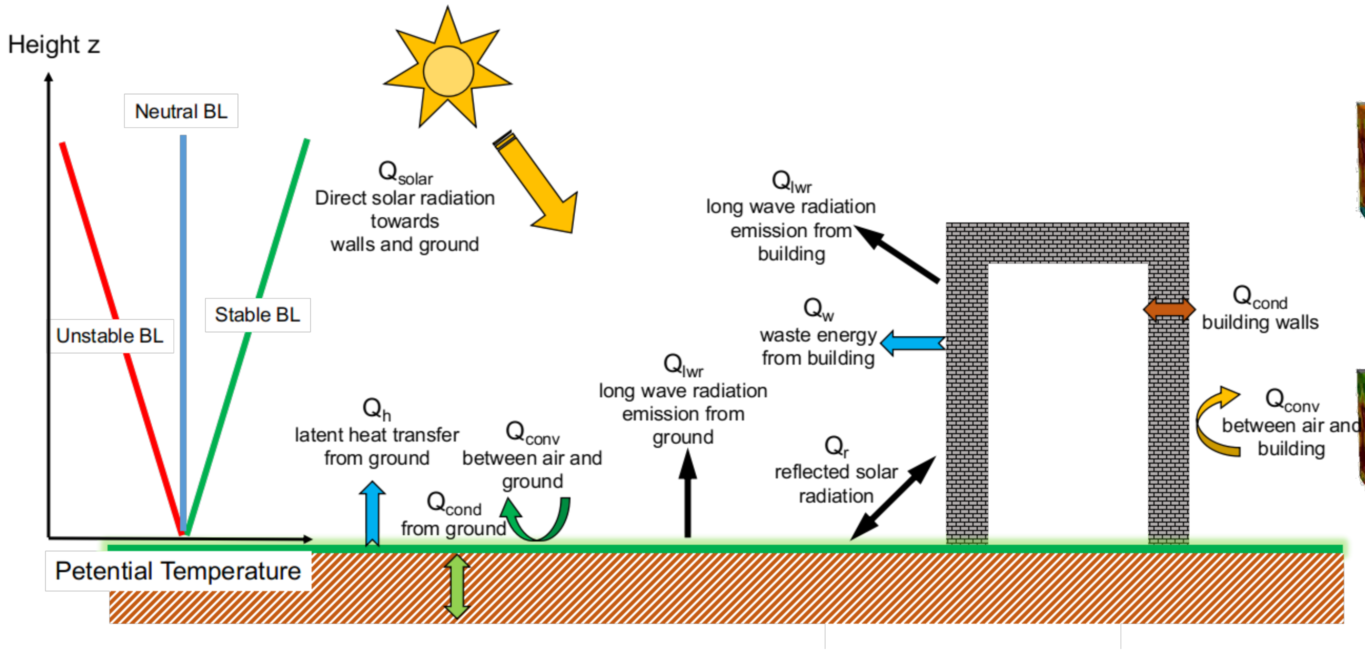
UNIVERSITY OF CAMBRIDGE

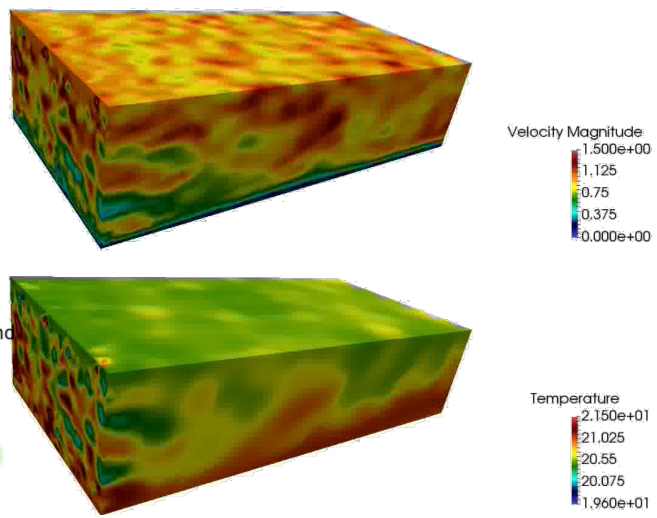
Towards more physics

Thermal effect - Microclimate

- Main factor influencing the urban microclimate

Laetitia Mottet



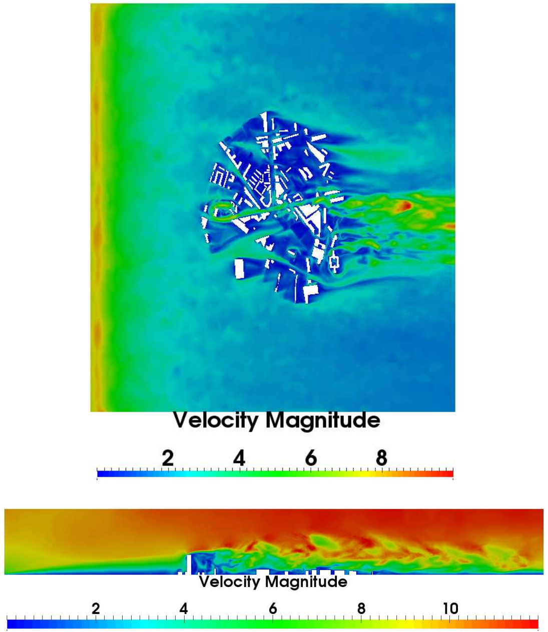


Towards fast numerical tool

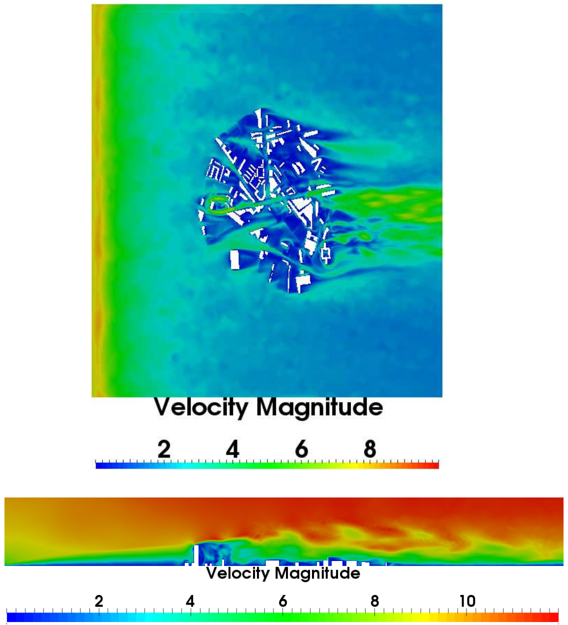
Non-Intrusive Reduced Order Model (NIROM)

Dunhui Xiao

- Ability of NIROM to reproduce the instantaneous velocity field

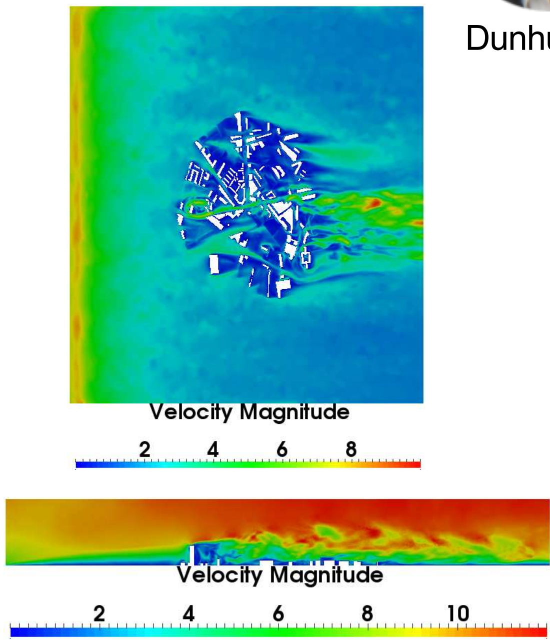


Full model



NIROM

96 basis function



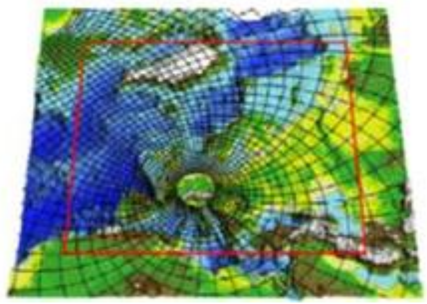
NIROM

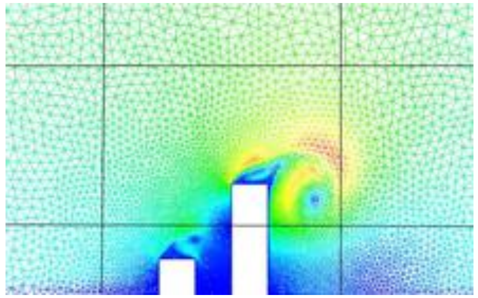
382 basis function

UNIVERSITY OF CAMBRIDGE

How

- What will this look like?
  - Fully integrated suite of models
  - Management tools
  - Decision support tools
- Comprised of:
  - Fully resolved air quality model
  - Reduced order model
  - Cost-benefit analysis
- MAGIC Circle: www.magic-air.uk





Conclusions

- Simulating airflow in buildings is critical to a sustainable future
- Direct numerical simulations remain
  - unachievable at full scale
  - difficult to match boundary conditions
- Approximate methods require
  - Comparison with laboratory studies
  - Comparison with field studies
- Many interesting challenges

UNIVERSITY OF CAMBRIDGE

With thanks to

STATE OF CALIFORNIA
ENERGY COMMISSION

NSF

THE ROYAL SOCIETY

erc
European Research Council
Established by the European Commission

EPSRC
Engineering and Physical Sciences Research Council

UNIVERSITY OF CAMBRIDGE