ICOS Cities
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Variability of physical meteorology in urban areas at different scales:
implications for observations and modelling

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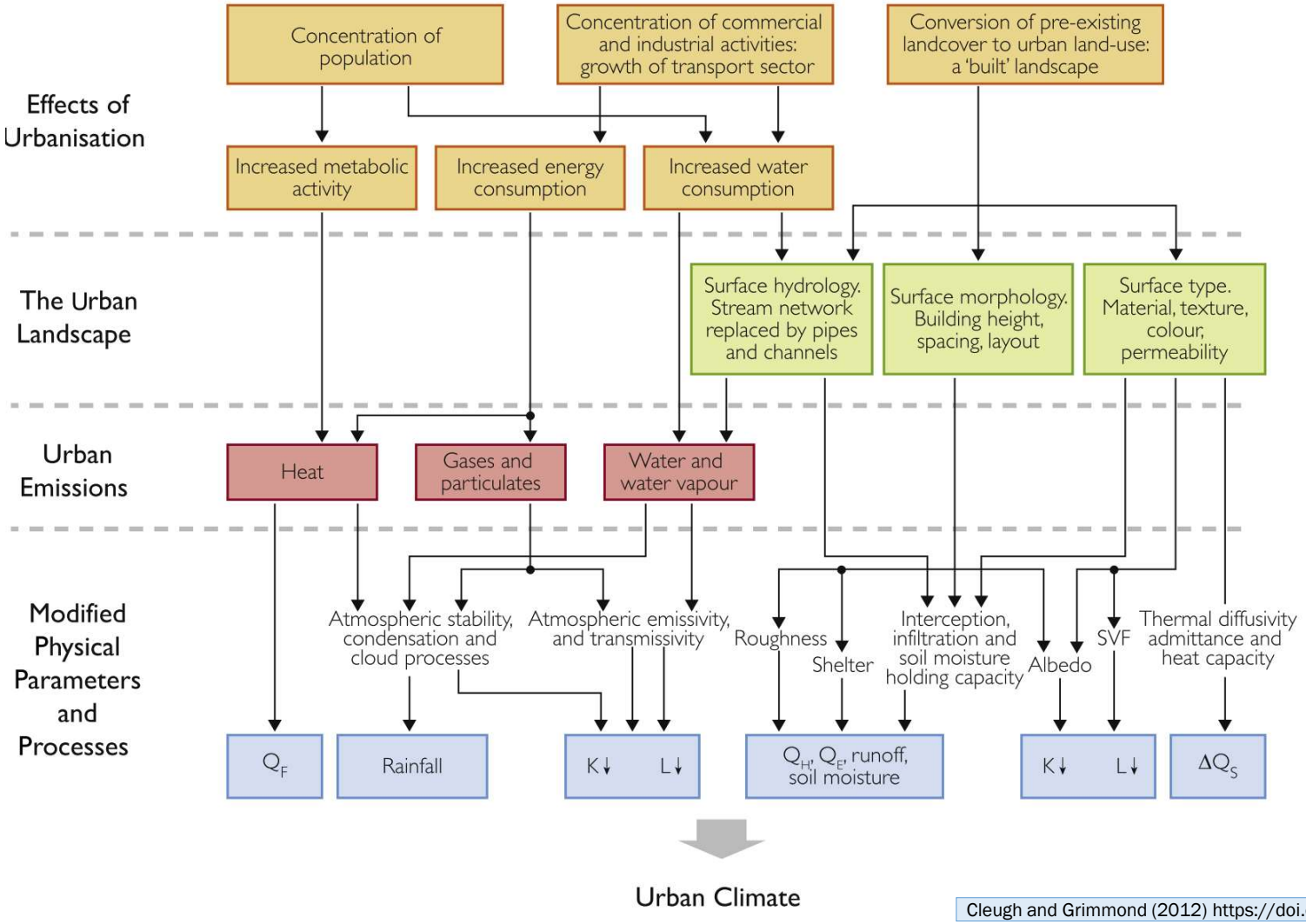
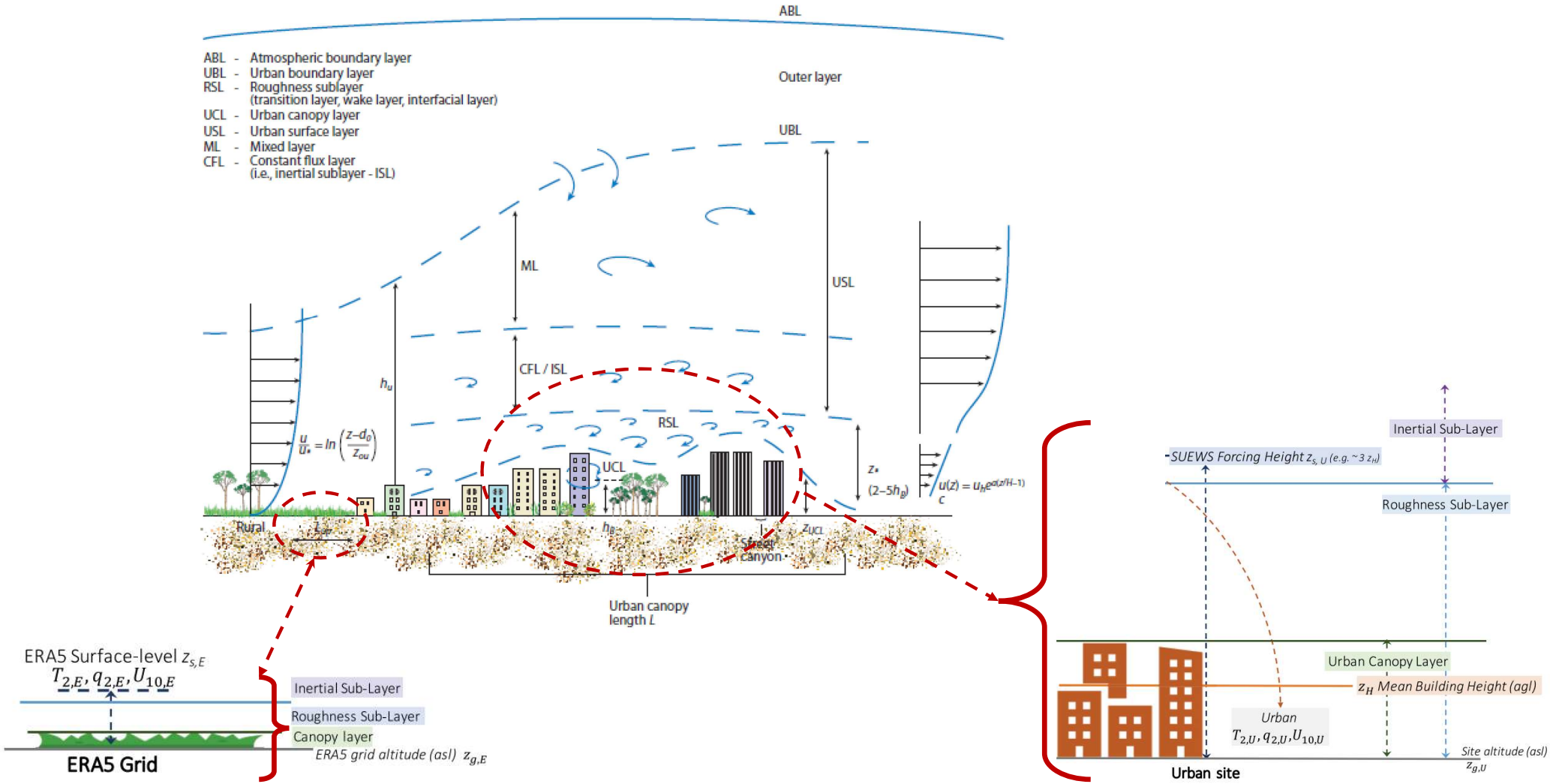
Urban Atmospheric Processes



Cleugh and Grimmond (2012) https://doi.org/10.1016/B978-0-12-386917-3.00003-8

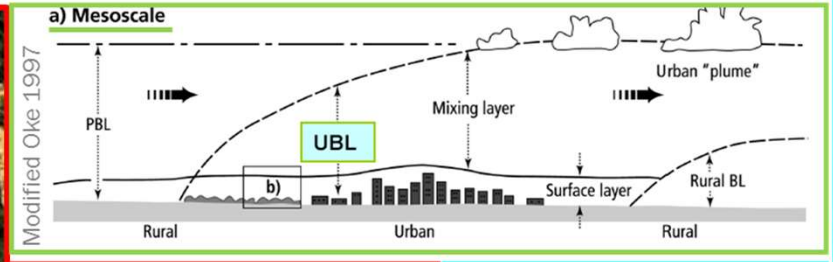


Fernando 2010: https://doi.org/10.1146/annurev-fluid-121108-145459

Tang et al. 2021: Building and Environment, https://doi.org/10.1016/j.buildenv.2021.108088

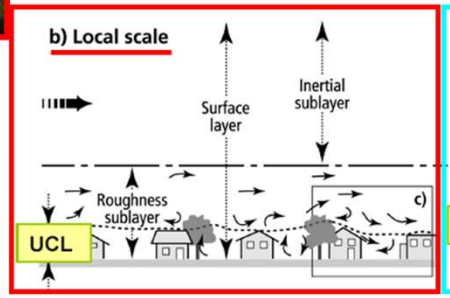
Challenge of scale

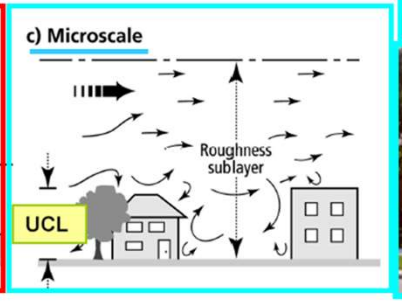
- Observe over relatively small areas
- Need to model (NWP, Climate, Applications) for complete city at an appropriate scale



Gothenburg

Chicago



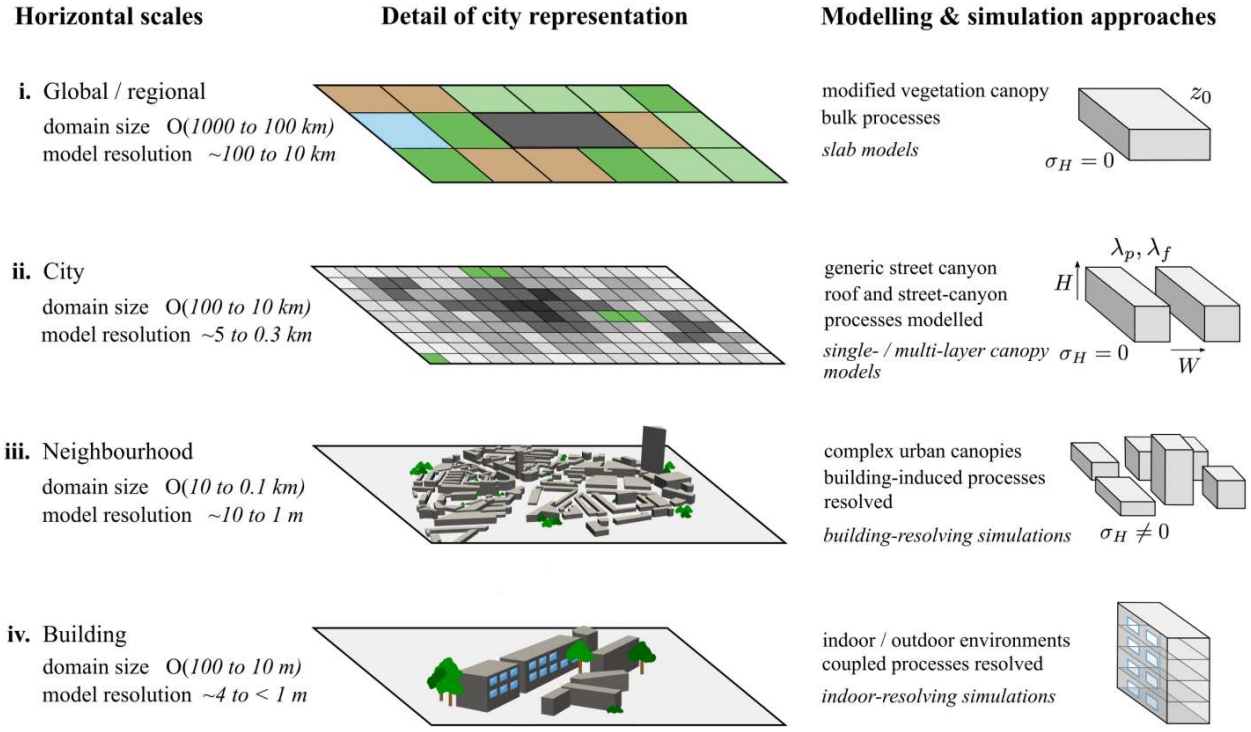


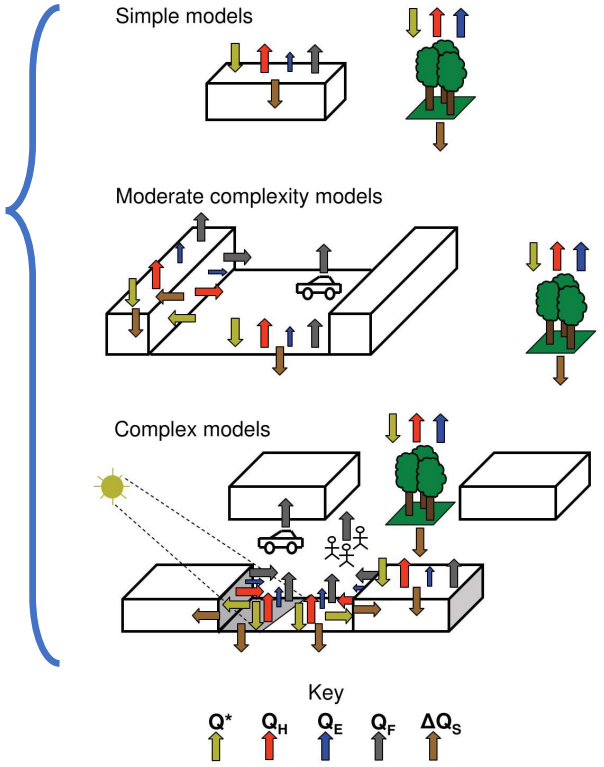
Numerous constraints or challenges in urban areas

Barlow et al. (2017) https://doi.org/10.1175/BAMS-D-17-0106.1

- MOST – breaks down close to the surface
- Urban roughness elements large
- Thermal and Visible remote sensing
  - coarse spatial scales or coarse temporal scales
  - + need clear skies
- Spatial heterogeneity
  - 3-d nature of the urban surface
- Anthropogenic effects
  - Behaviour change heat and mass exchanges

Modelling: Climate, Weather, Planning, Building Design



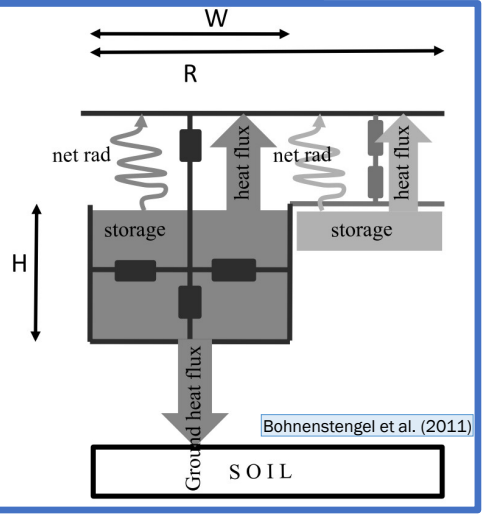


Hertwig et al. (2021) https://doi.org/10.1002/joc.7018

Best and Grimmond (2015) https://doi.org/10.1175/BAMS-D-14-00122.1

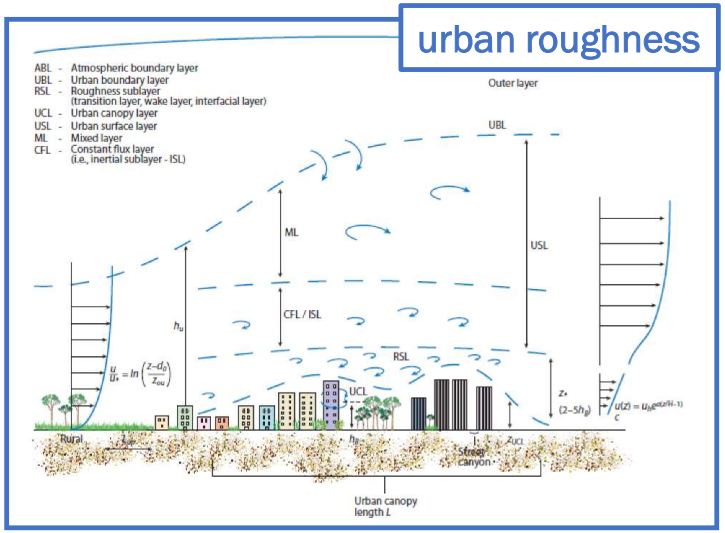
Urban Characteristics

urban morphology

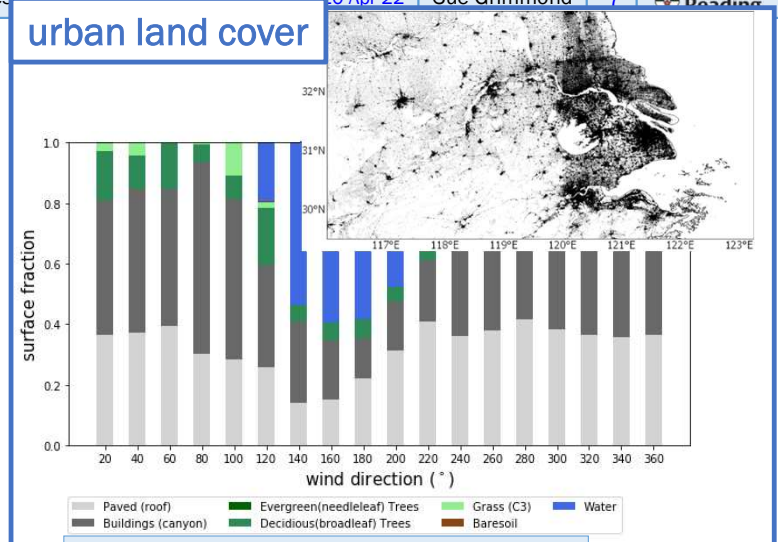


Bohnenstengel et al. (2011)

urban roughness



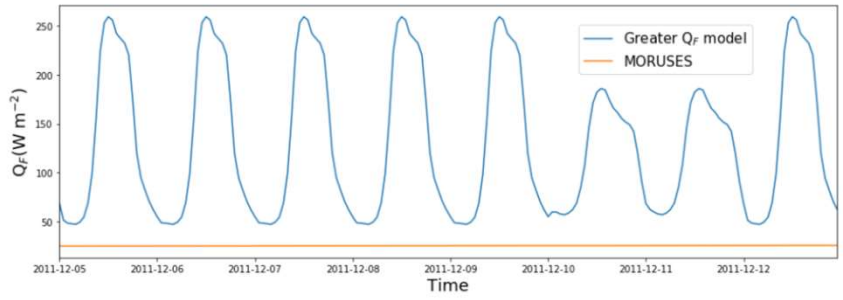
urban land cover



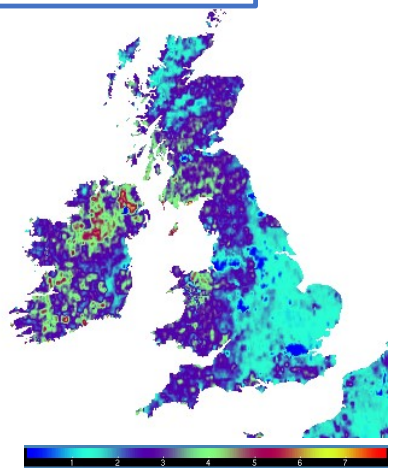
Hertwig et al. (2021) https://doi.org/10.1002/joc.7018

anthropogenic heat

Treated as parameter- should be dynamic

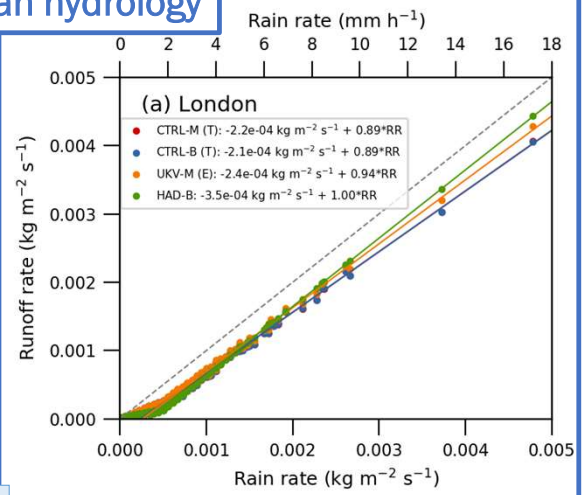


urban phenology



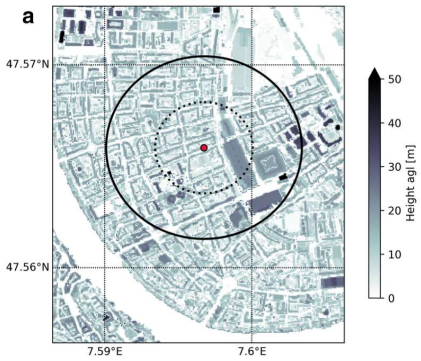
Hertwig et al. (2021) *TAAC* https://doi.org/10.1007/s00704-020-03294-1

urban hydrology



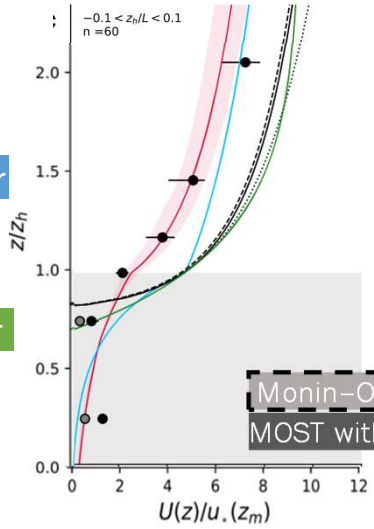
Real World Observations: Basel

Basel-Sperrstrasse



Roughness sub layer

Urban Canopy Layer

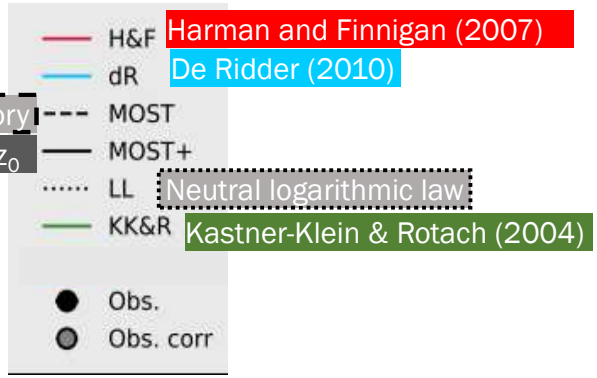


Near neutral

Wind across flat-roof buildings

Monin–Obukhov similarity theory

MOST with stability dependent z_0

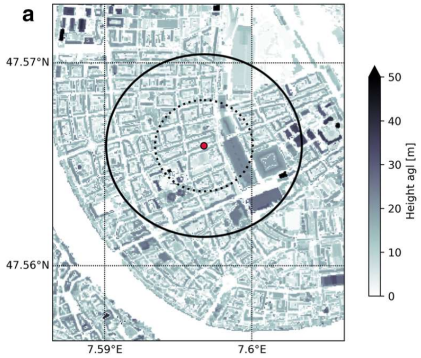


Profiles of Wind speed normalized by friction velocity

Theeuwes *et al*. (2019) *BLM* https://doi.org/10.1007/s10546-019-00472-1

Real World Observations: Basel & Gothenburg
Different stabilities

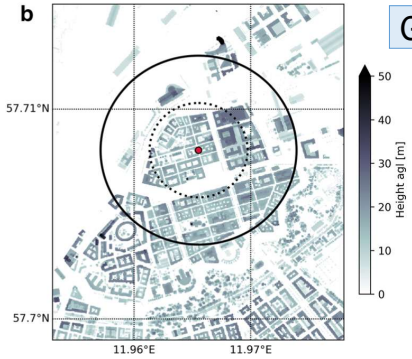
Basel-Sperrstrasse



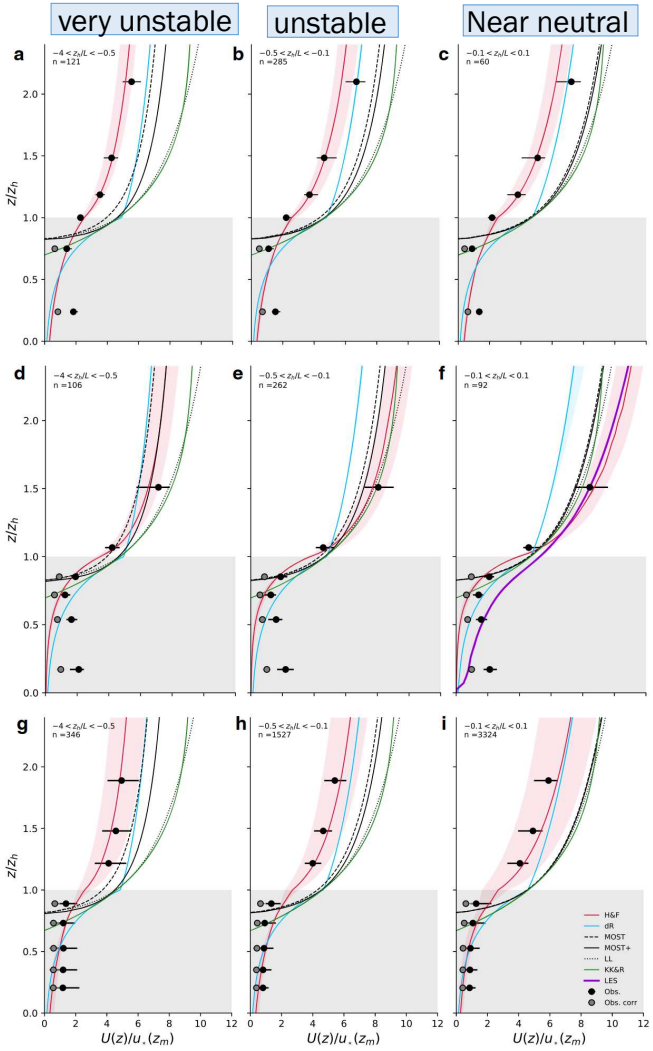
flat-roof buildings

pitch-roof buildings

Gothenburg



perpendicular to the street canyon



Wind speed profiles normalized by friction velocity

H&F Harman and Finnigan (2007)
dR De Ridder (2010)
MOST Monin–Obukhov similarity theory
MOST+ MOST with stability dependent z_0
LL Neutral logarithmic law
KK&R Kastner-Klein & Rotach (2004)
LES Giometto et al. (2016) LES
Obs.
Obs. corr

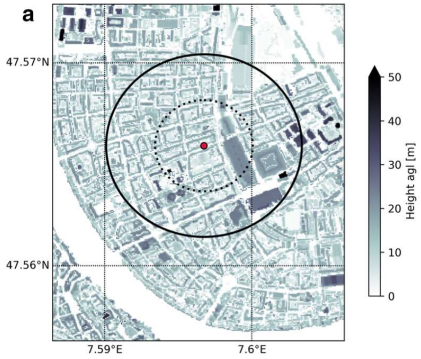
Theeuwes *et al.* (2019) *BLM* https://doi.org/10.1007/s10546-019-00472-1

Real World Observations: Basel & Gothenburg
Different stabilities

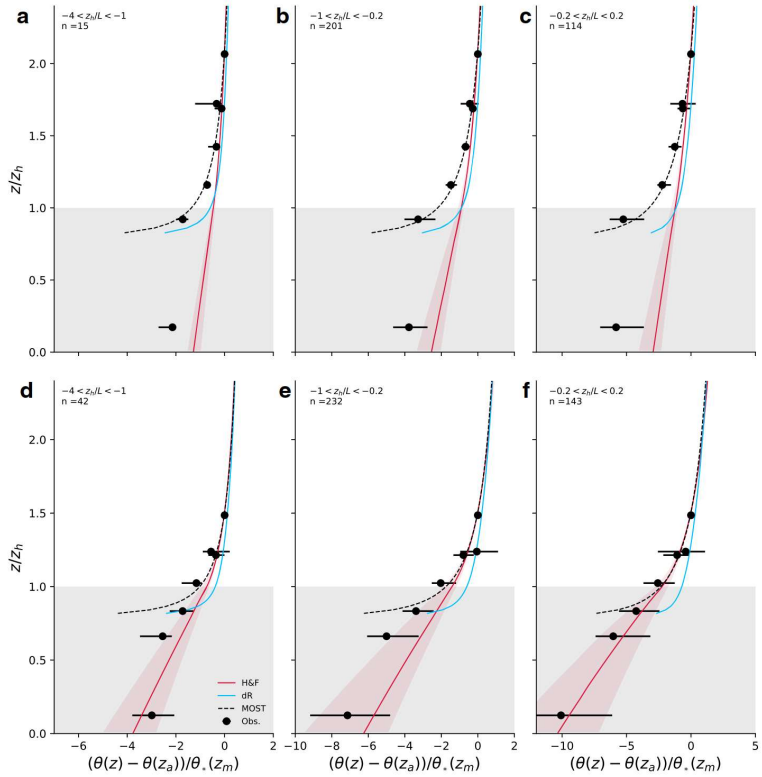
Basel-Sperrstrasse

flat-roof buildings

pitch-roof buildings



very unstable | unstable | Near neutral

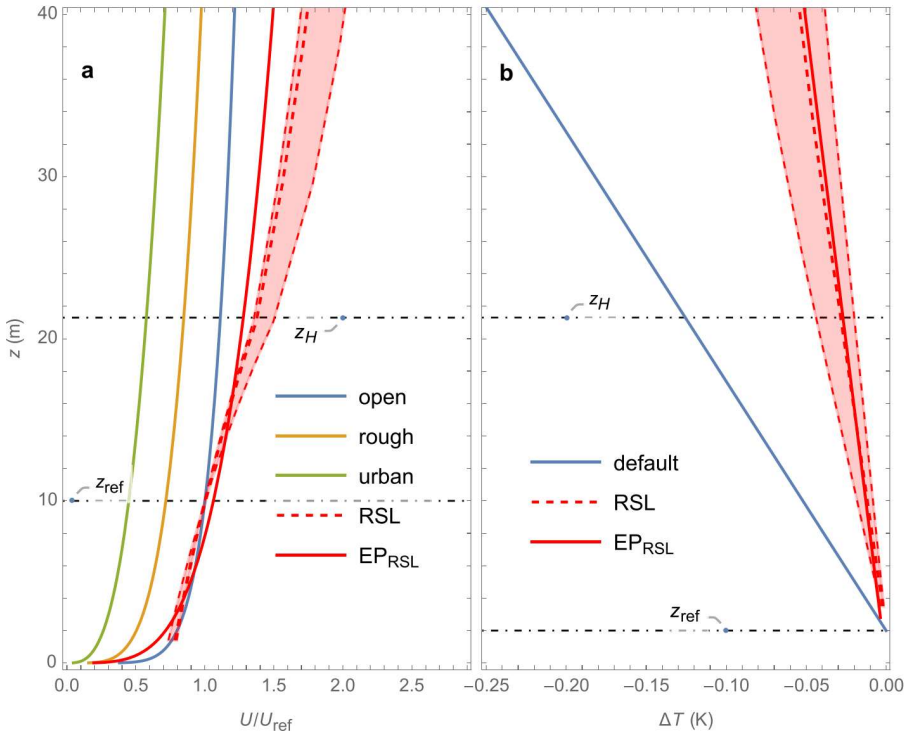


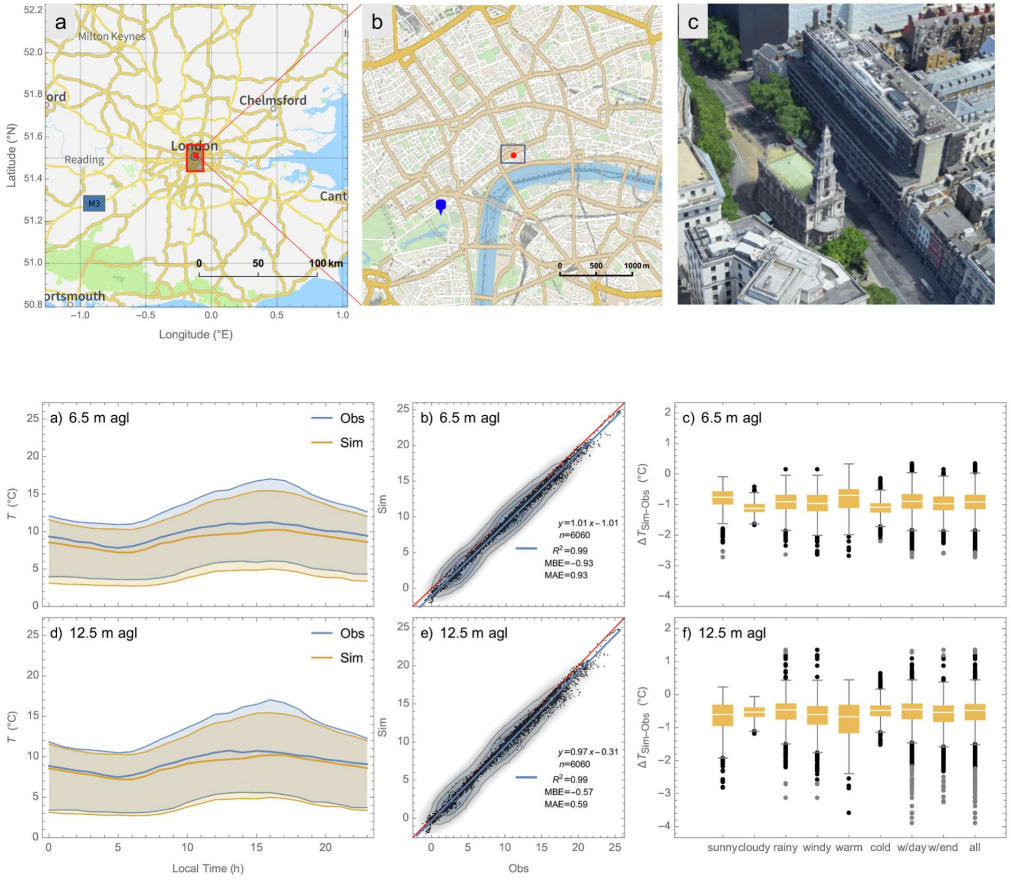
Temperature Profile

H&F Harman and Finnigan (2007)
dR De Ridder (2010)
MOST Monin–Obukhov similarity theory
Obs.

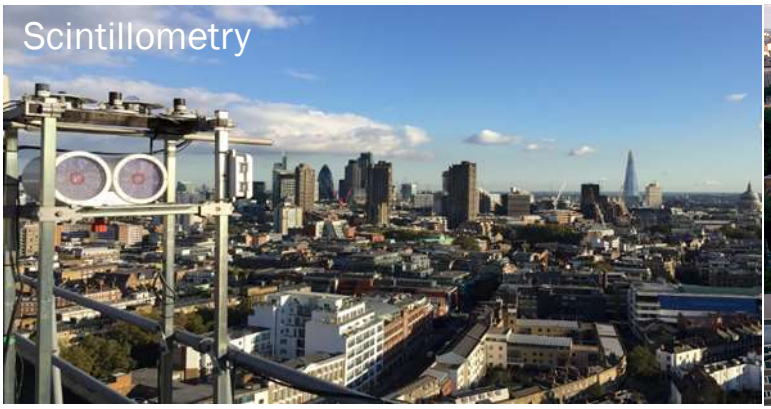
Theeuwes *et al.* (2019) *BLM* https://doi.org/10.1007/s10546-019-00472-1

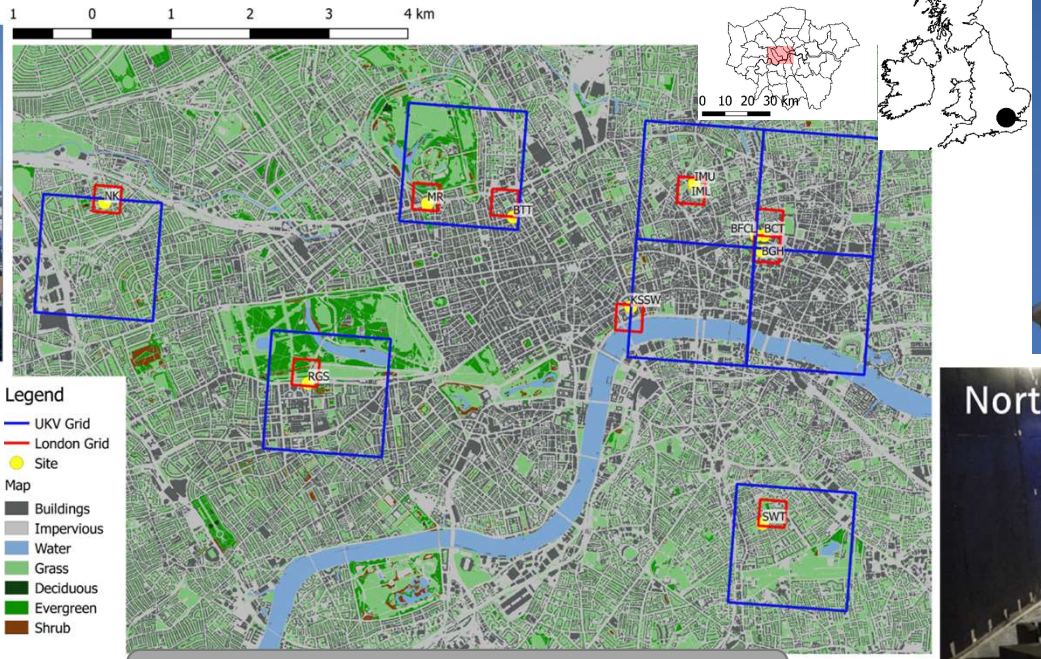
SUEWS: RSL Profile Evaluation in London





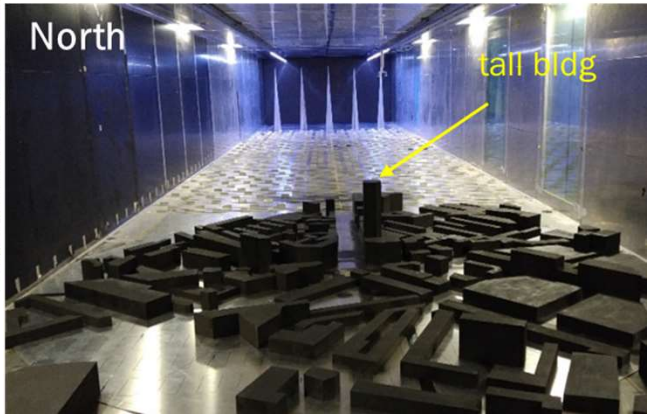
Tang et al. 2021: Building and Environment, https://doi.org/10.1016/j.buildenv.2021.108088





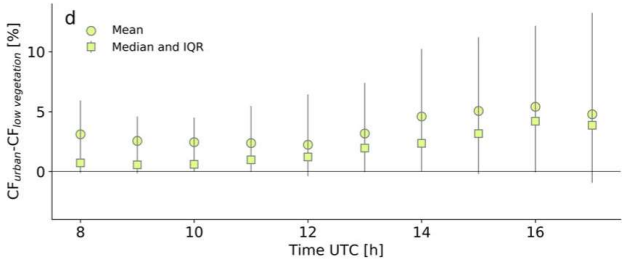
Ceilometer/ALC

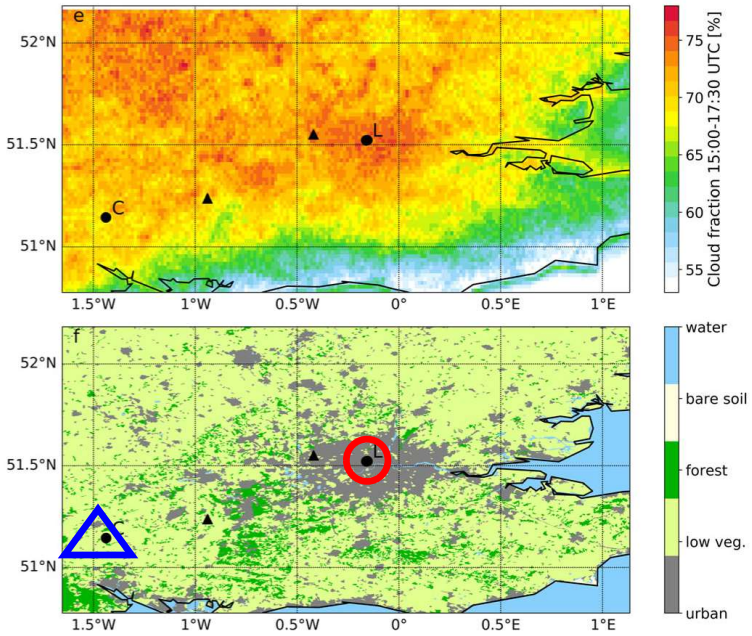
Urban Meteorology Observations



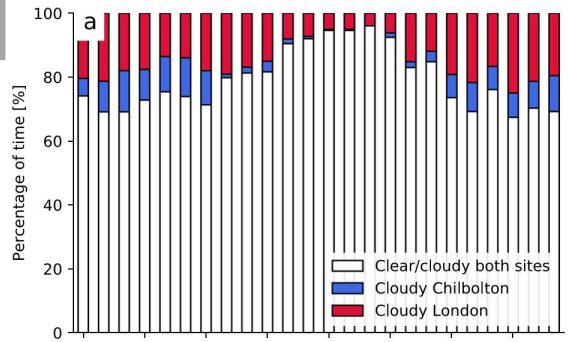
Urban & Rural Cloud

- MSG –HRV Satellite

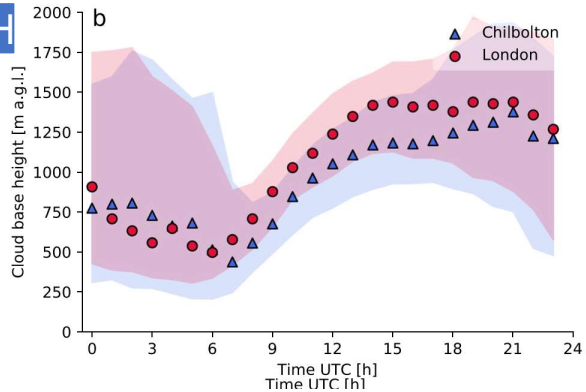




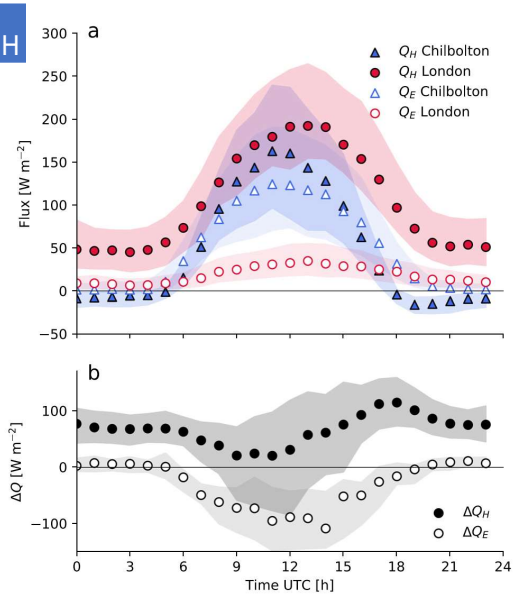
% of time cloudy



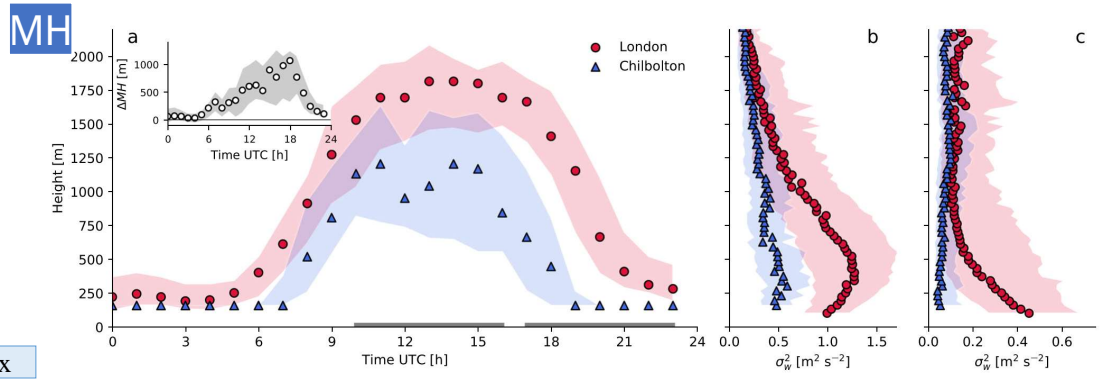
CBH



Q_H

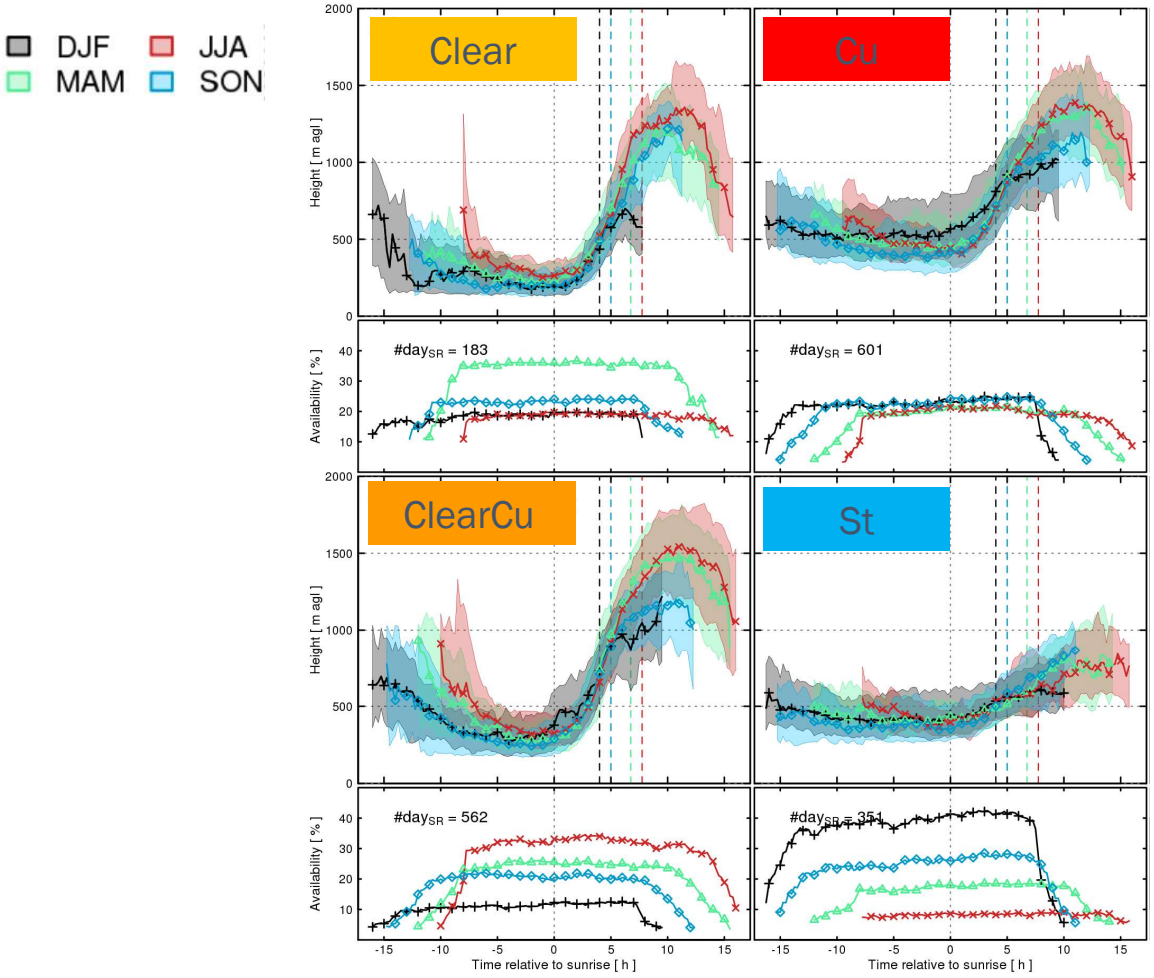


MH



Theeuwes et al. (2019) npj CAS https://doi.org/10.1038/s41612-019-0072-x

London

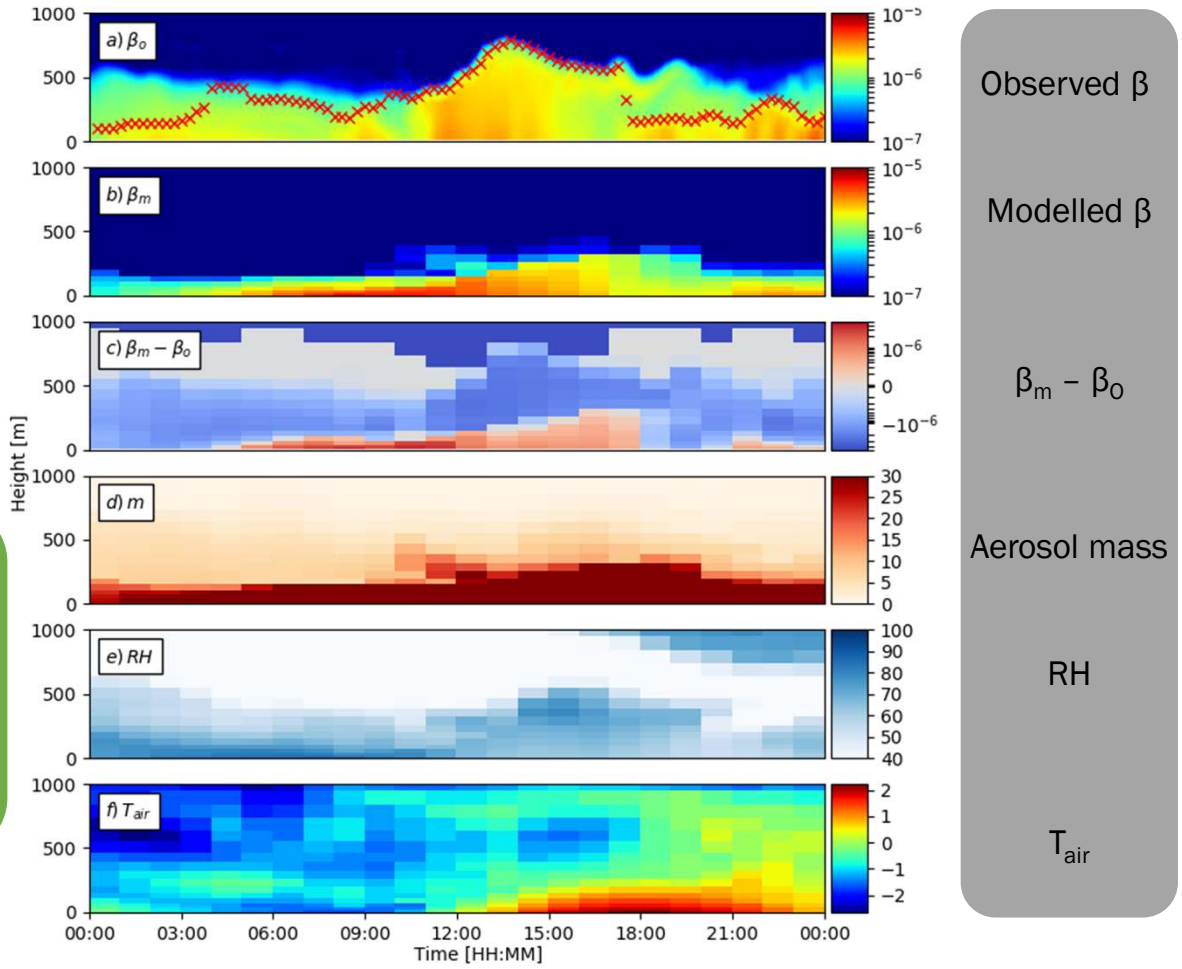


- Lower for clear nights
- Highest for *Cu* days
- Morning growth rates:
  - Strongest - for *ClearCu*
  - Weakest – for *St*

Kotthaus and Grimmond 2018b QJRMS https://doi.org/10.1002/qj.3298

High pollution case (19 January 2016)

- Observed daily average PM_{10} > 50 µg m^{-3}
- UKV with Best-1T scheme

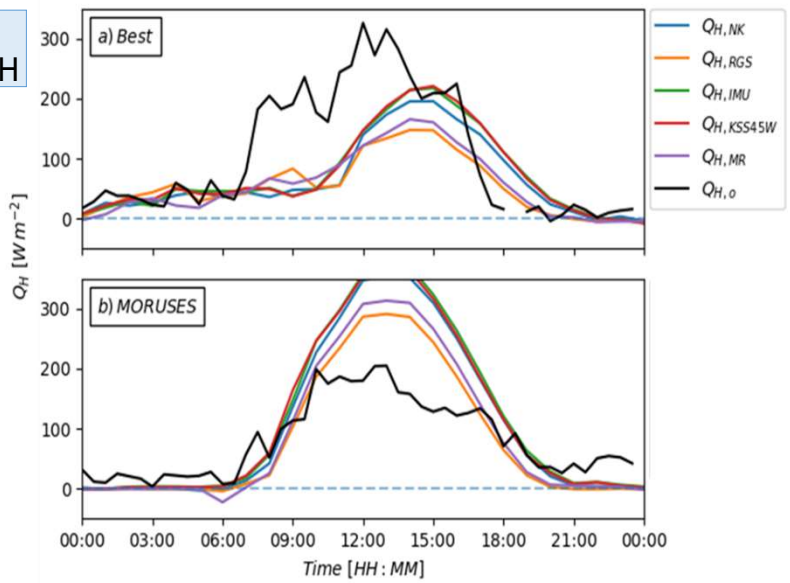


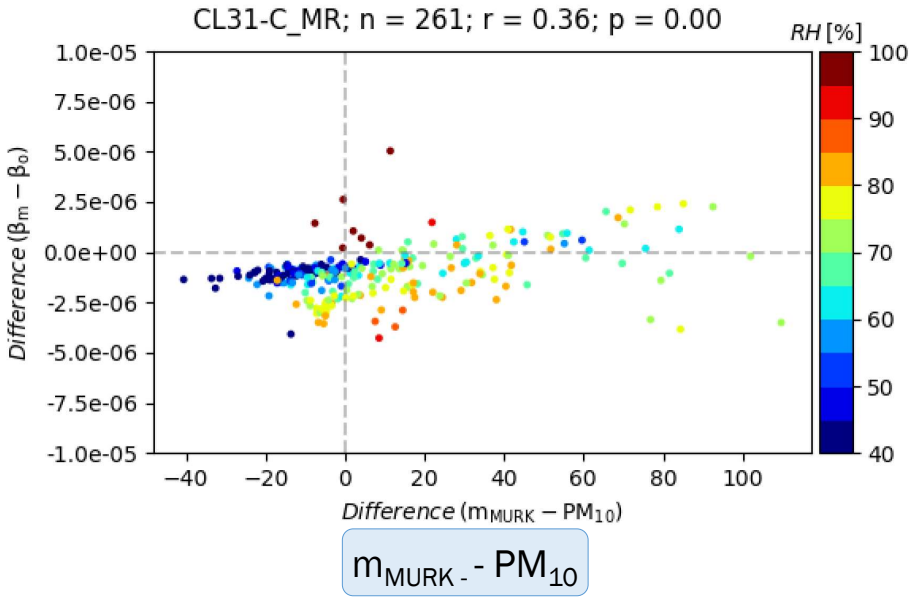
- Almost persistently high β_m near the surface
- Aerosol: insufficiently mixed in the vertical due to **lack of aerosol dispersion**
- Earlier dates – could identify emission inventory problems

Warren et al. (2018) https://doi.org/10.1016/j.atmosenv.2018.04.045

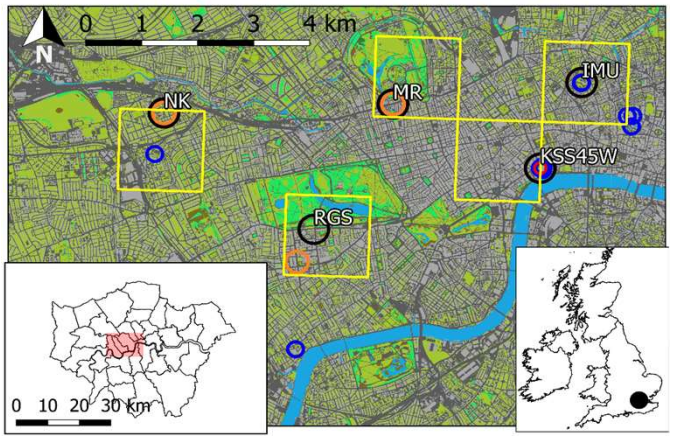
Other near surface evaluation

Q_H





m_{MURK} - PM_{10}



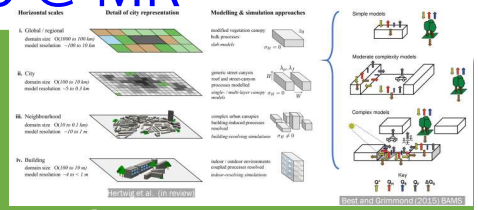
- Point difference in attenuated backscatter ($\Delta\beta = \beta_m - \beta_o$) near the surface difference in total mass ($\Delta m = m_{MURK} - PM_{10}$) [$PM_{10}$ a proxy]
- Suggests aerFO underestimates attenuated backscatter
- β_m - most accurate during drier conditions (RH – point colour)
  - Error in RH - becomes more important at high RH due to $f_{RH,ext}$

Warren et al. (2018) https://doi.org/10.1016/j.atmosenv.2018.04.045

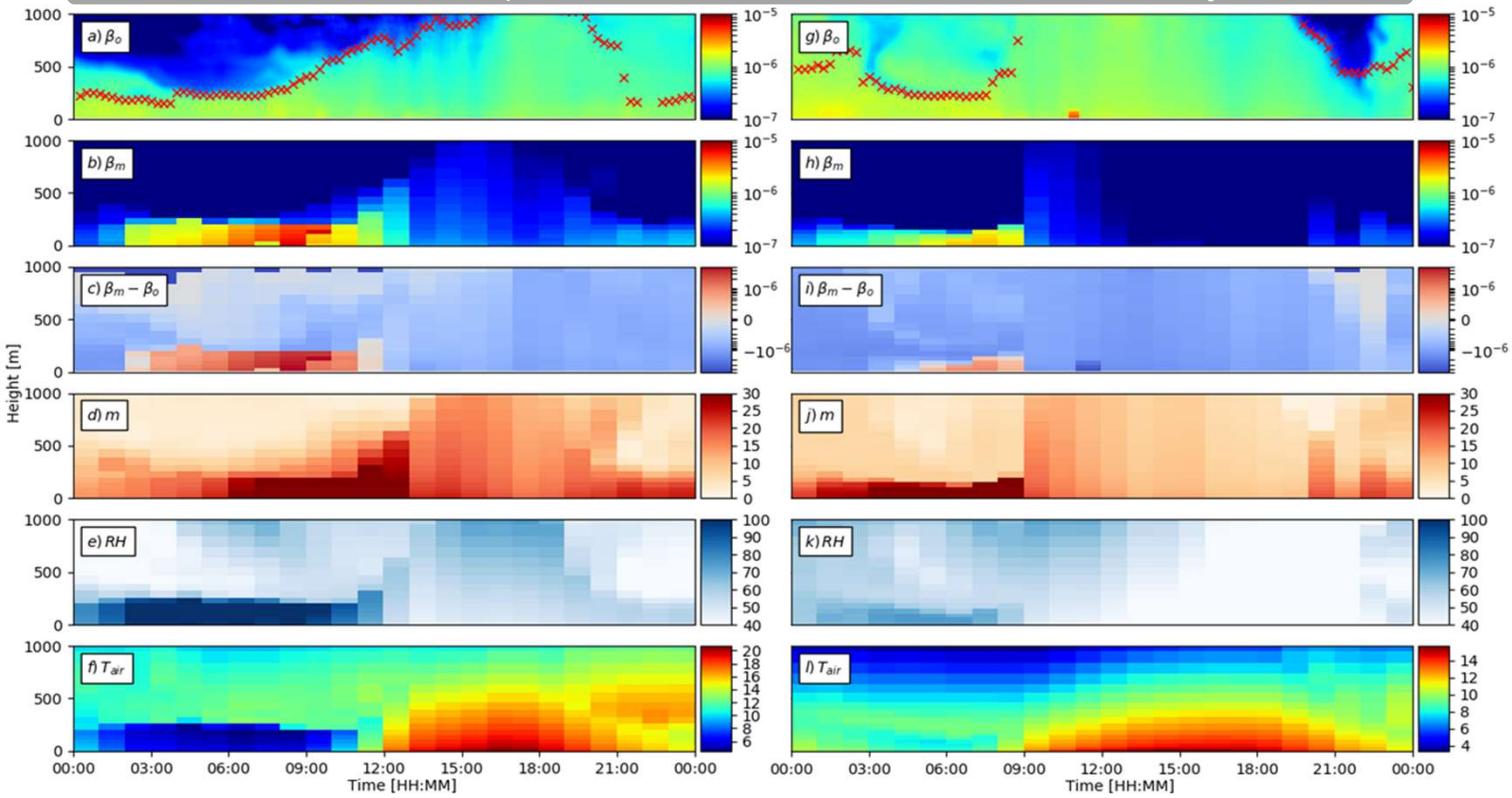
Impact of changing model dynamics on β_m assessed with aerFO @ MR

- Urban surface scheme change in **UKV:**
  - Best 1-tile → MORUSES *(15/Mar/16)*

- Morning near-surface β_m
  - 1-tile - high throughout
  - MORUSES – less
- Cold surface bias →delayed vertical mixing of m_{MURK} and high RH



Best 1 tile - 14 April 2015 | **MORUSES** - 04 May 2016



Observed β

Modelled β

$\beta_m - \beta_O$

Aerosol mass

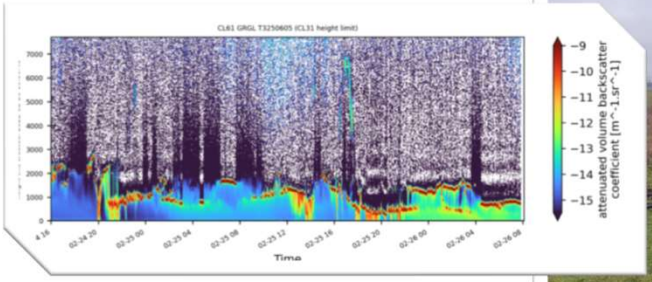
RH

T_{air}

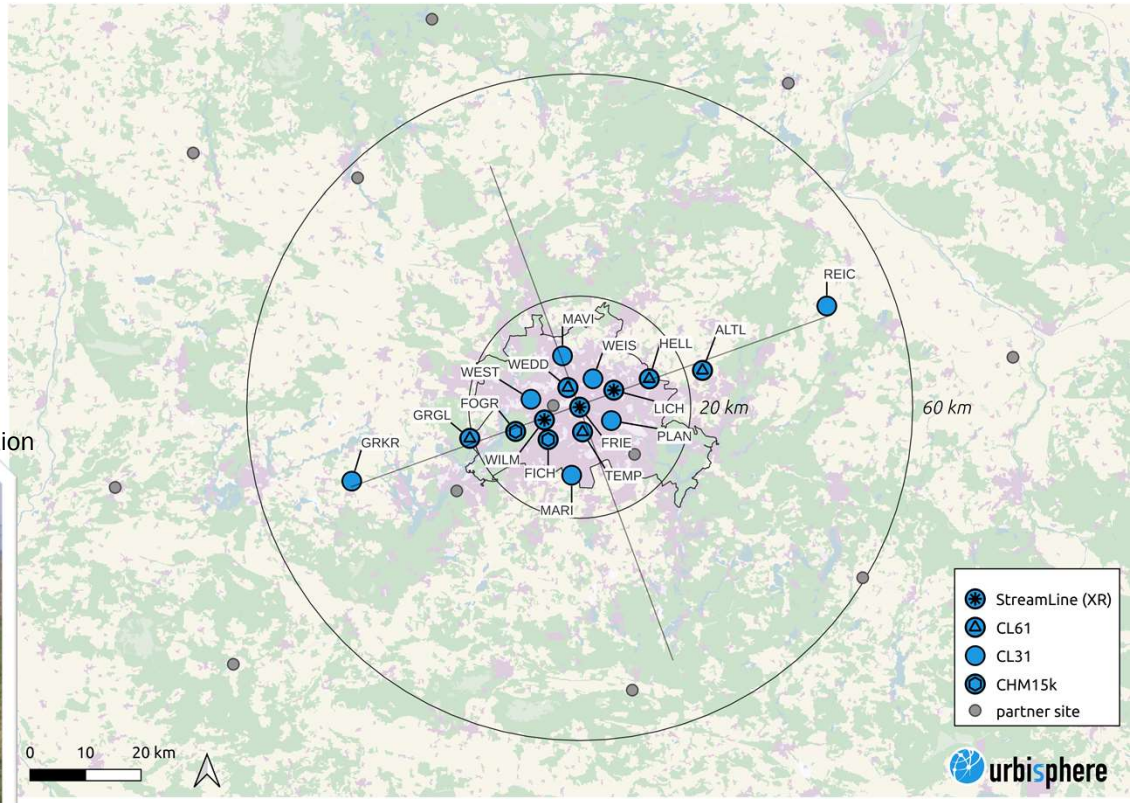
Warren et al. (2018) https://doi.org/10.1016/j.atmosenv.2018.04.045

Berlin: Automatic LiDAR and ceilometer (ALC) network

- quantify 3-dimensional modification
- internal variability of aerosol, mixed-layer dynamics and clouds as air flows across this urban area



Five sites Vaisala CL61 with depolarization



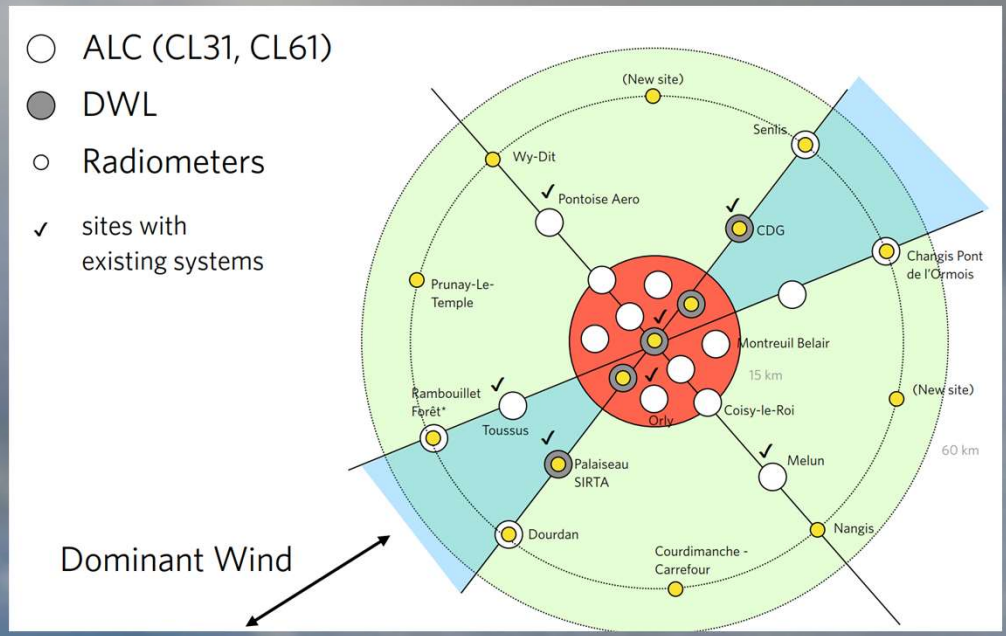
- 12 ALCs
- + 12 existing operational ALC systems
- Provide: cloud, attenuated aerosol backscatter
- From this mixed-layer heights and AOD can be derived

urbisphere

Next field campaign - Paris (late 2022 – late 2023)

- After Berlin
- SmUrObs to be deployed in Paris
- synergies with projects:
- GHG projects - ICOS, Actris
- Pre-Olympics campaigns – Meteo France, WMO

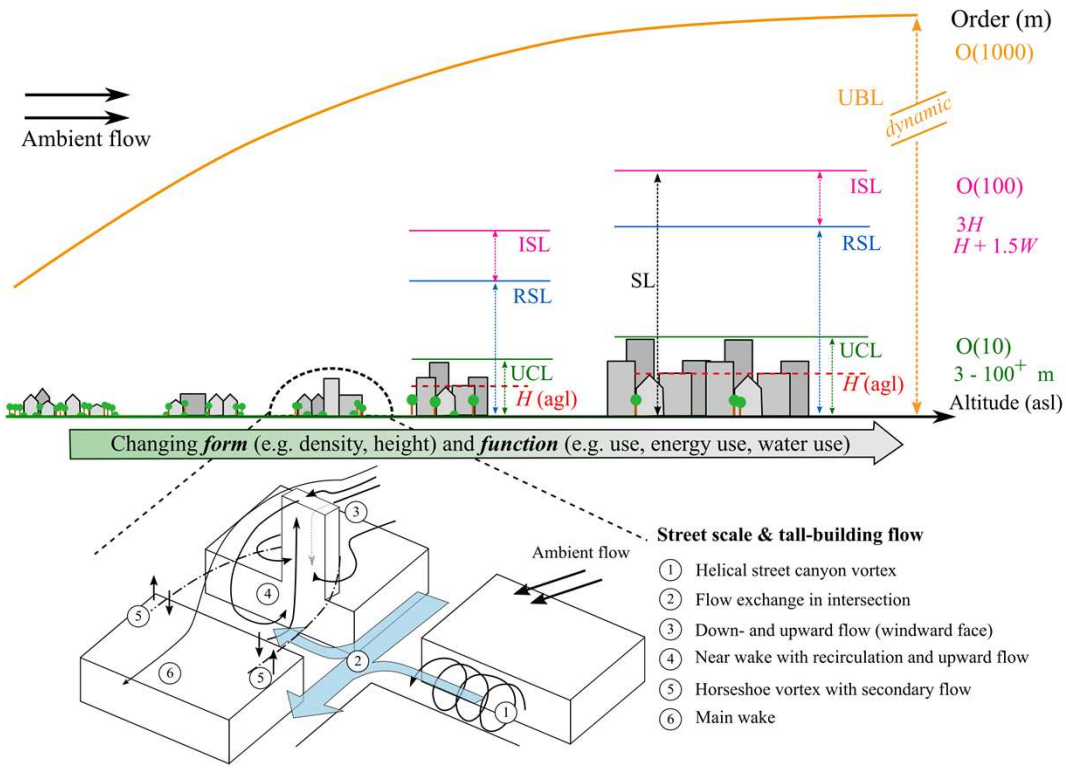
- Paris
- ‘isolated’ city
- 12 million people in metropolitan area

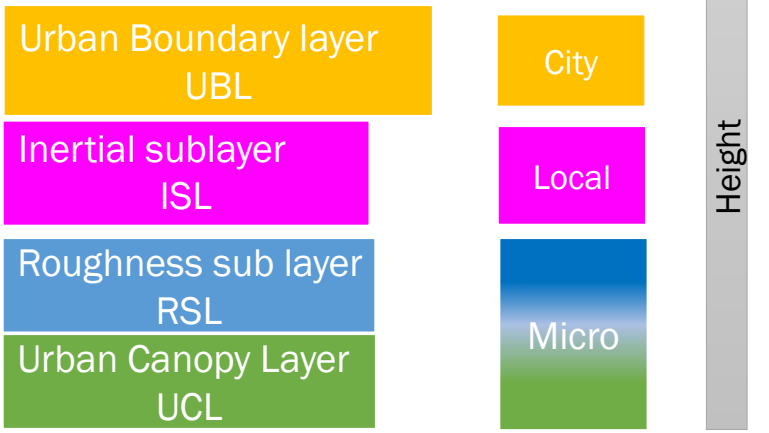


Contact us for more information

urbisphere

Scales in the urban atmosphere

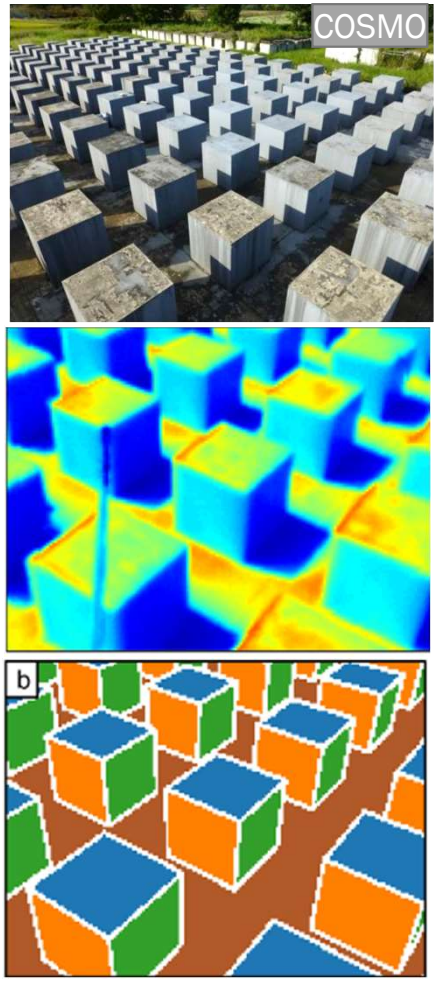




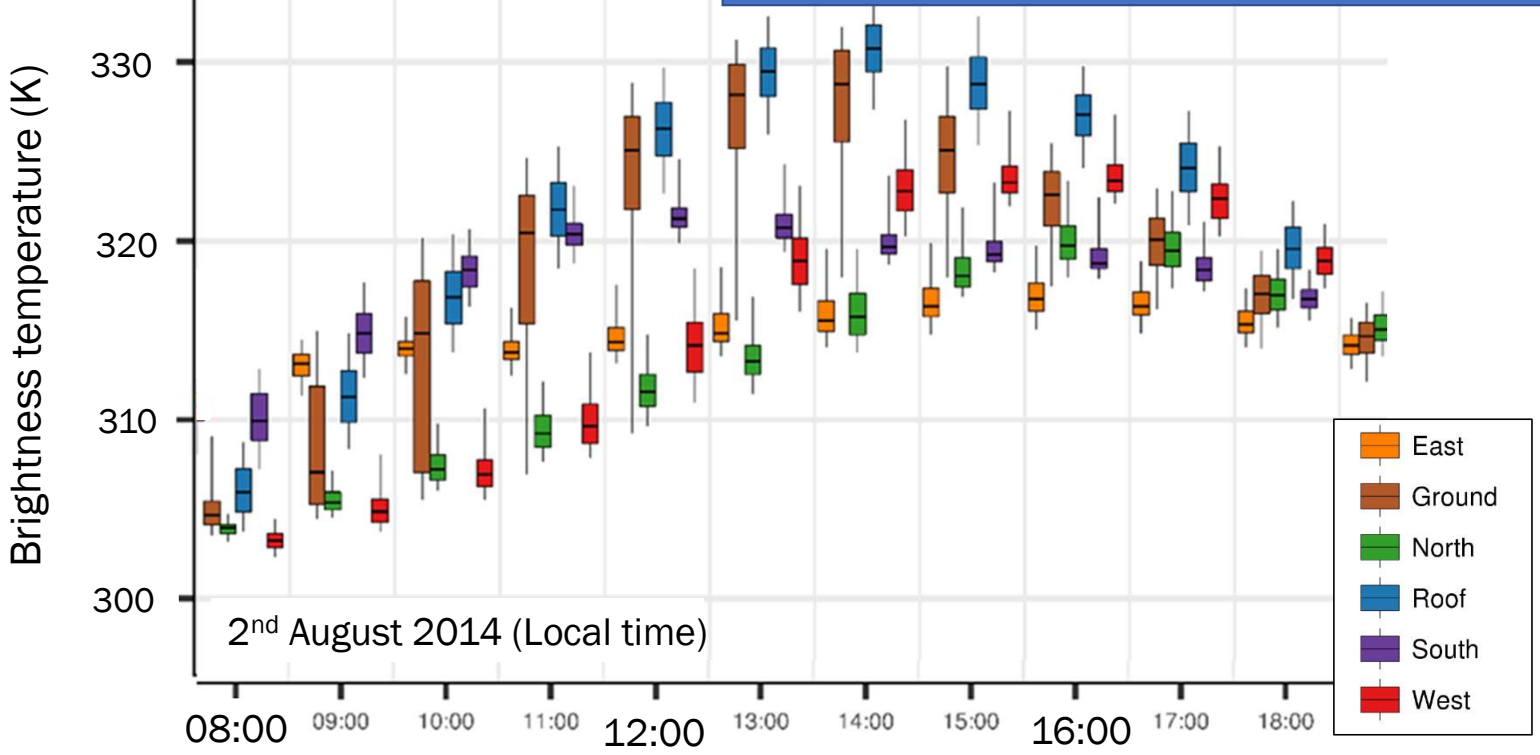
Hertwig et al. (2021) *Variability of physical meteorology in urban areas at different scales: implications for air quality*. Faraday Discussions https://doi.org/10.1039/D0FD00098A

Micro-scale: Controls on variability of surface temperature

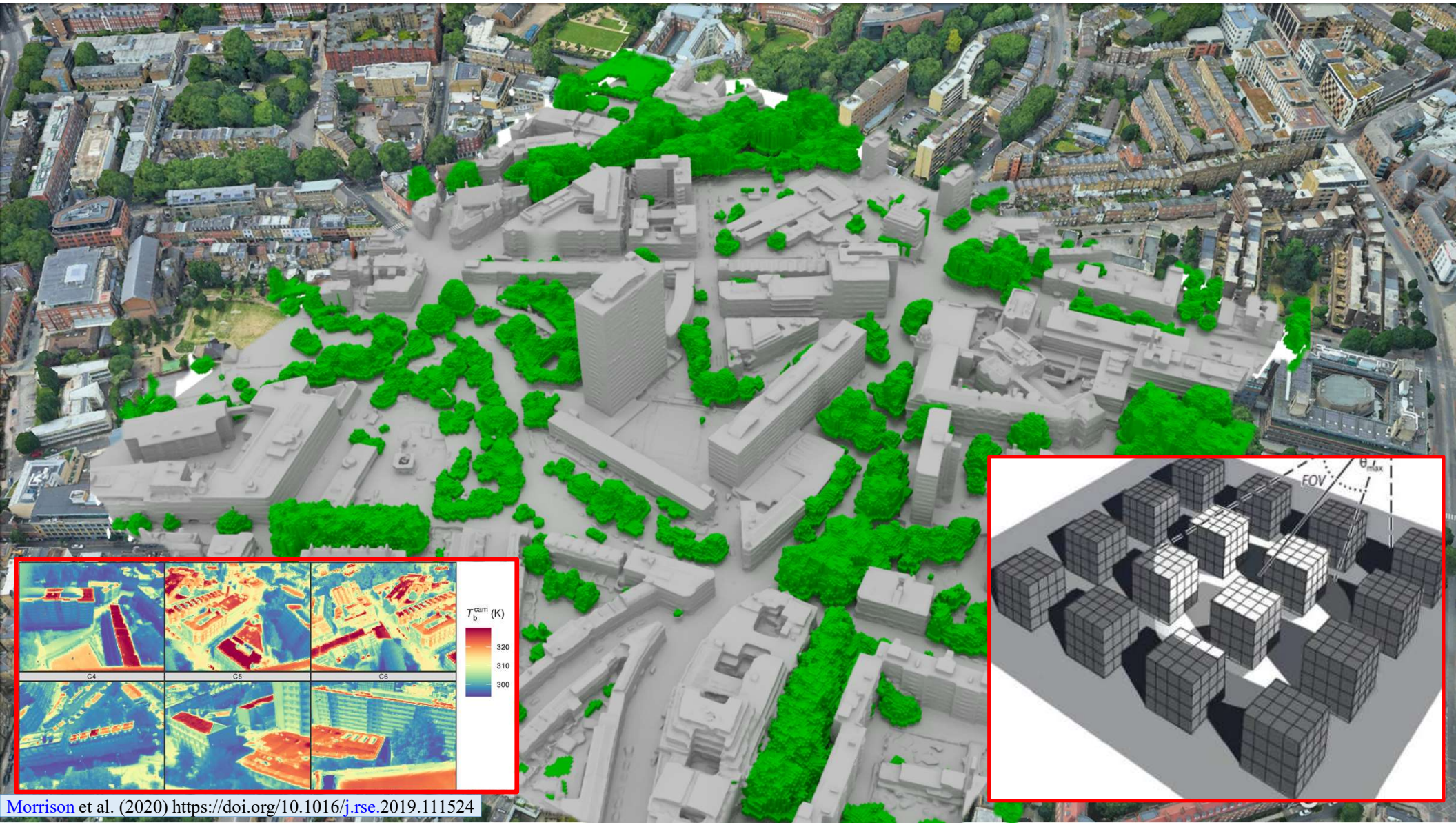
- Facet orientation



- Brightness temperatures differ by over 30 K
- Ground highly variable from shadows
- Most variability in morning
- More isothermal in afternoon

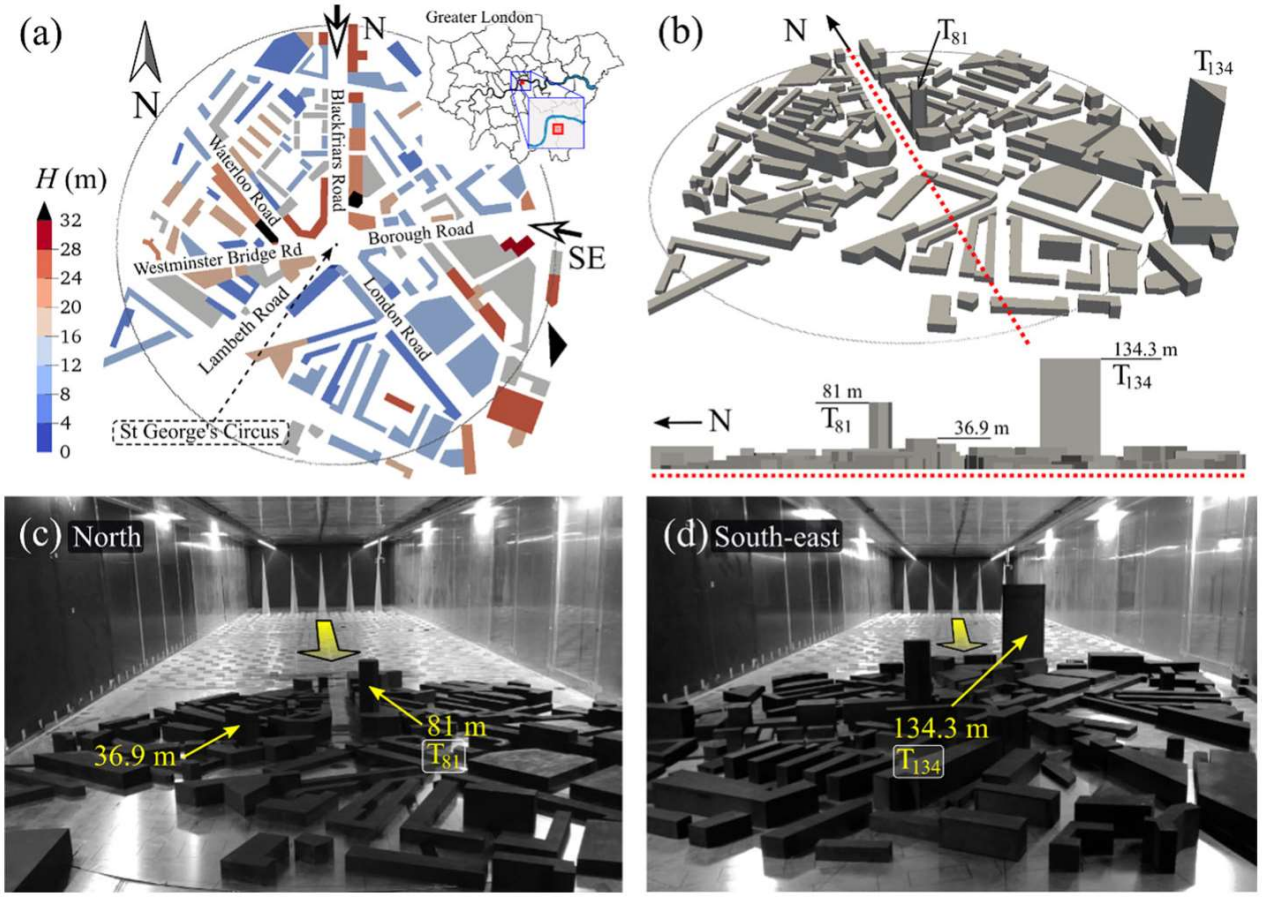


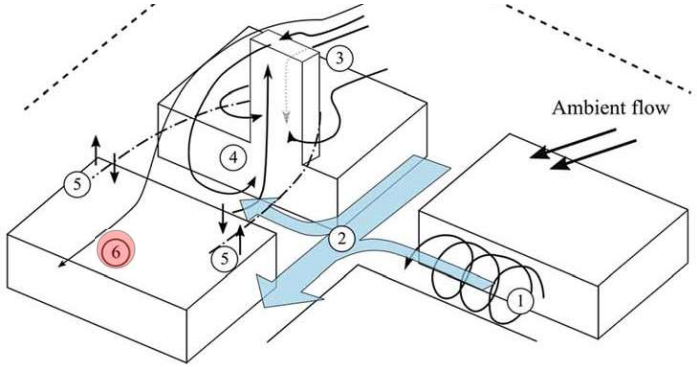
Morrison *et al*. 2018 *https://doi.org/10.1016/j.rse.2018.05.004*



Morrison et al. (2020) https://doi.org/10.1016/j.rse.2019.111524

Wind Tunnel (*EnFlo, University of Surrey*): Isolated Tall Buildings (London)





Street scale & tall-building flow

1. Helical street canyon vortex
2. Flow exchange in intersection
3. Down- and upward flow (windward face)
4. Near wake with recirculation and upward flow
5. Horseshoe vortex with secondary flow
6. Main wake

Hertwig *et al*. (2019) *BLM* https://doi.org/ 10.1007/s10546-019-00450-7
Hertwig et al. (2021) *Faraday Discussions* https://doi.org/10.1039/D0FD00098A

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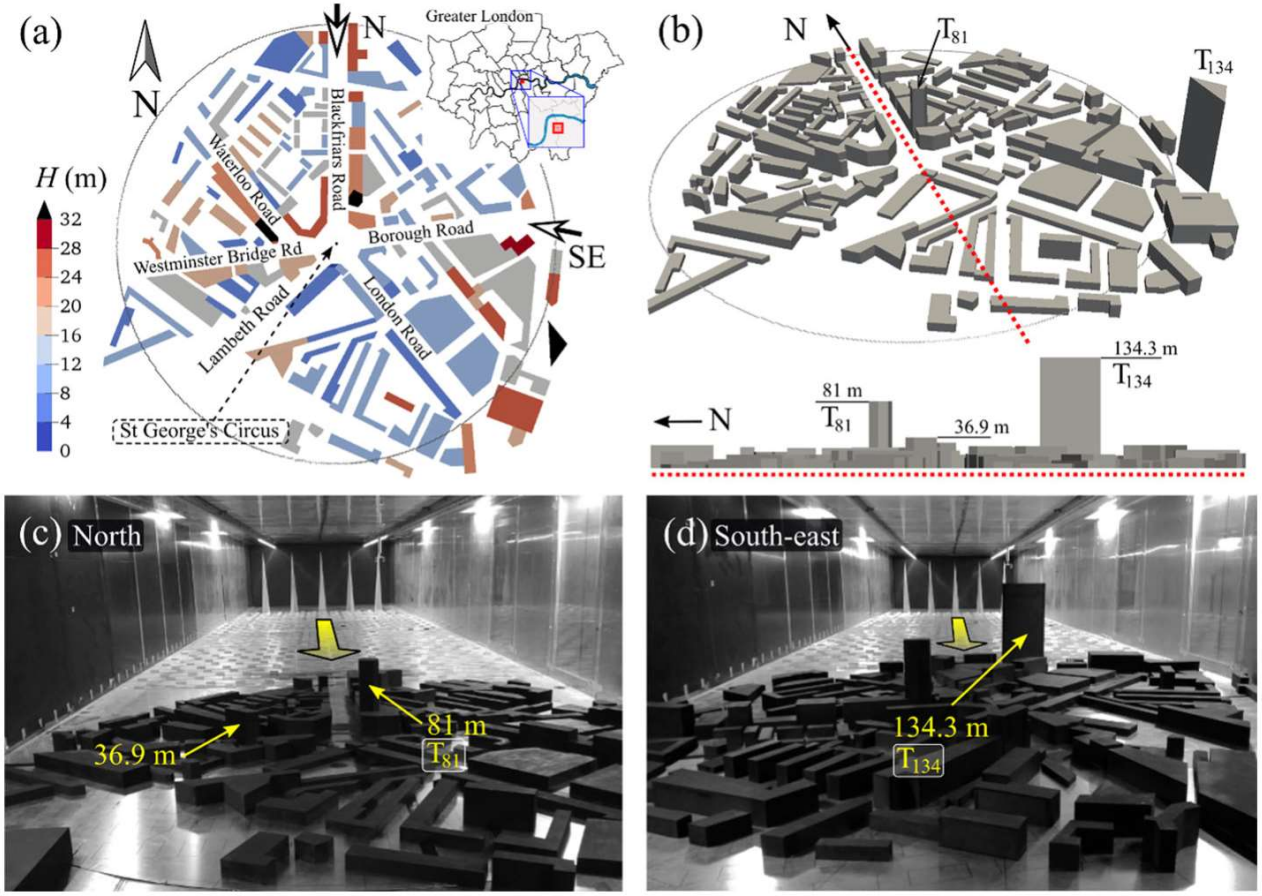

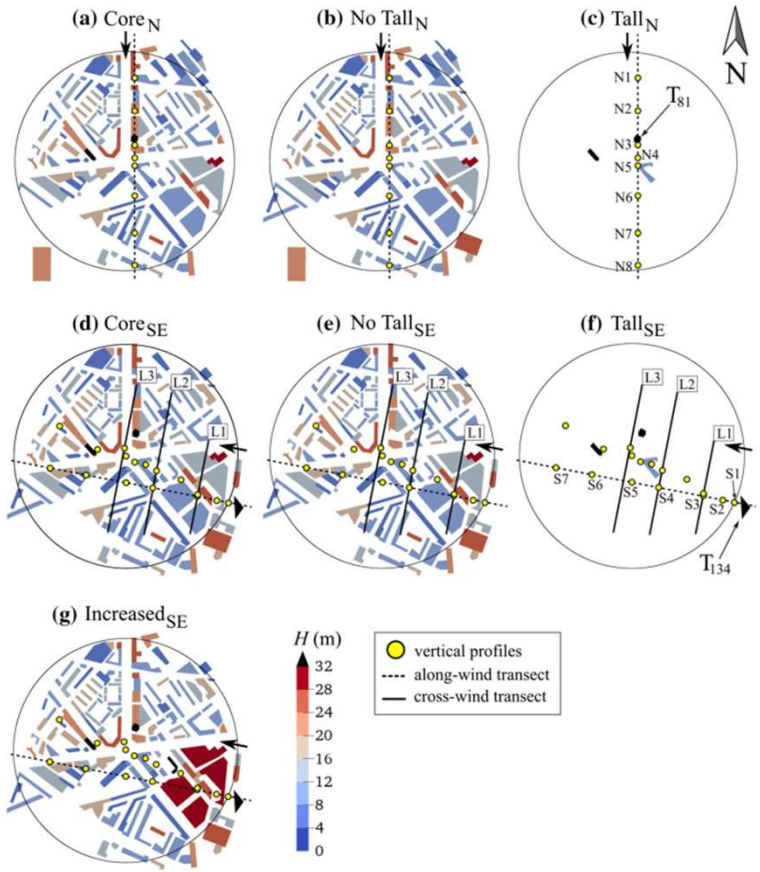

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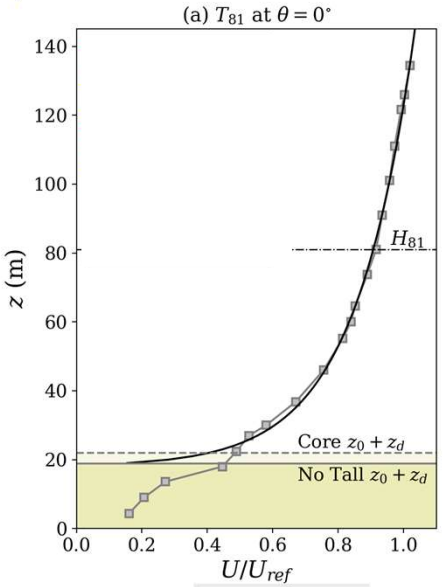
Isolated Tall Buildings (TB): London

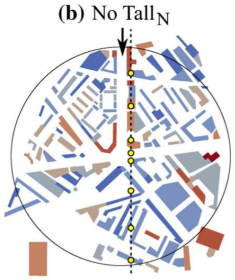
Profiles of mean longitudinal (along-wind) velocity (U/U_{ref}) ensemble averages

Micro

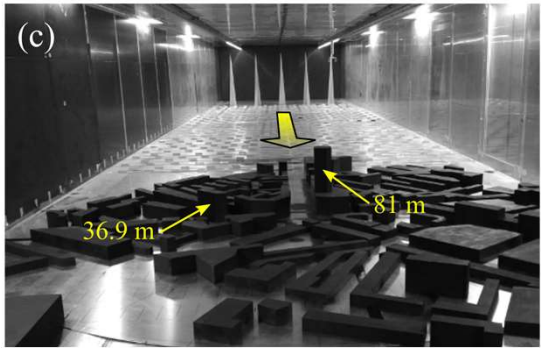
Roughness sub layer

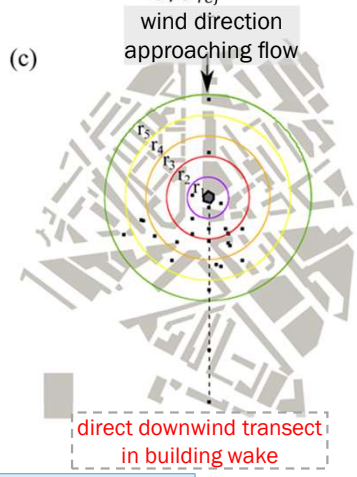
Urban Canopy Layer





all sites (No Tall)
log-law fit (No Tall)





- Measurement locations
  radii (arcs, colour) - *increments of 0.5 H_{TB}*

Distances from tall building

- $r_1 = 0.5H_T$
- $r_2 = 1.0H_T$
- $r_3 = 1.5H_T$
- $r_4 = 2.0H_T$ (T_{81} only)
- $r_5 = 2.5H_T$
- $r_6 = 3.0H_T$ (T_{134} only)
- $r_7 = 3.5H_T$ (T_{134} only)
- $r_8 = 4.0H_T$ (T_{134} only)

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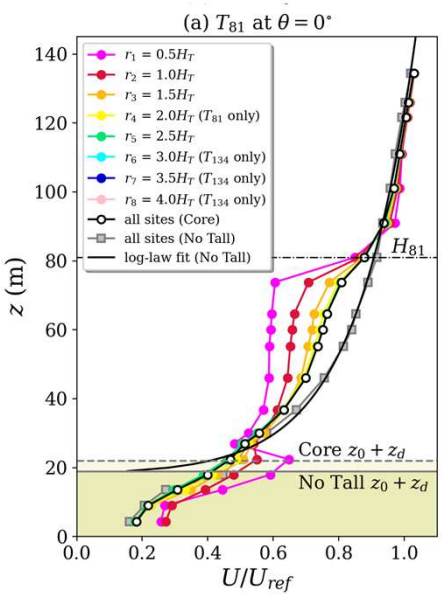

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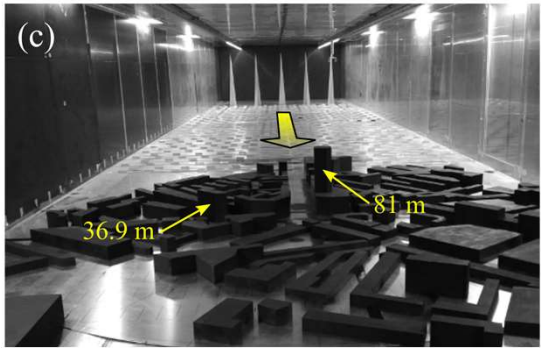

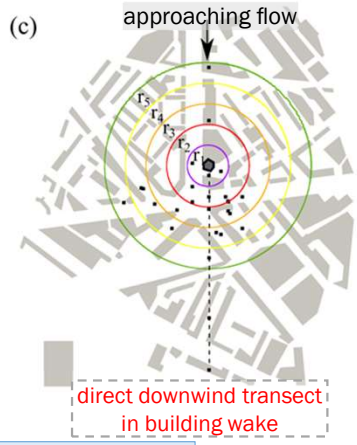

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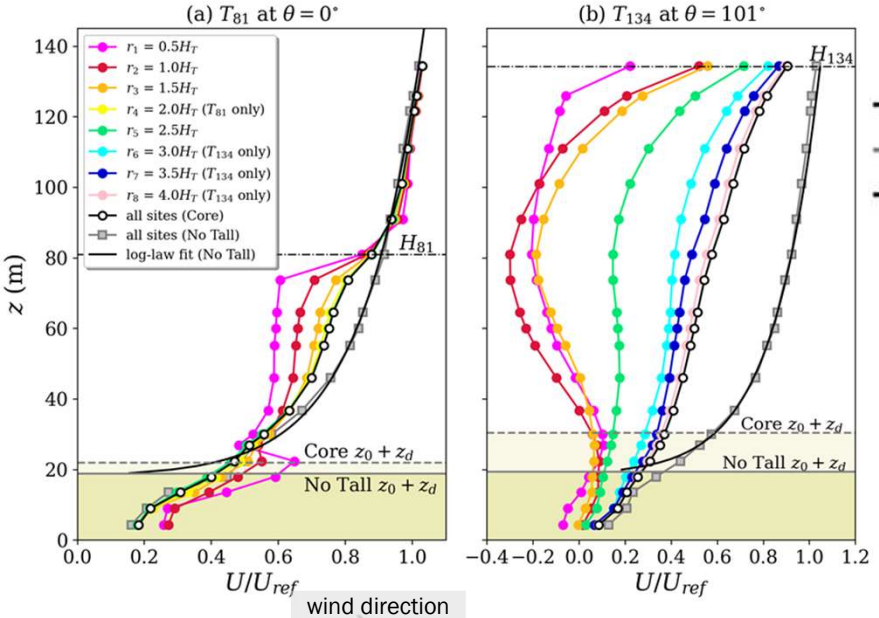

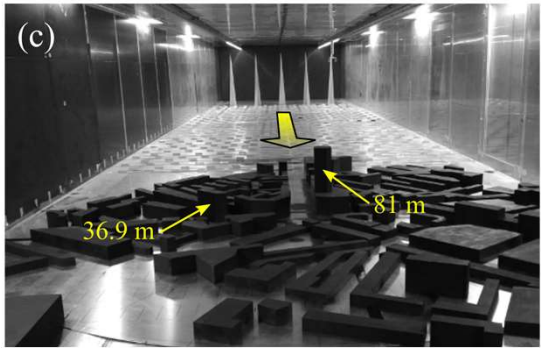

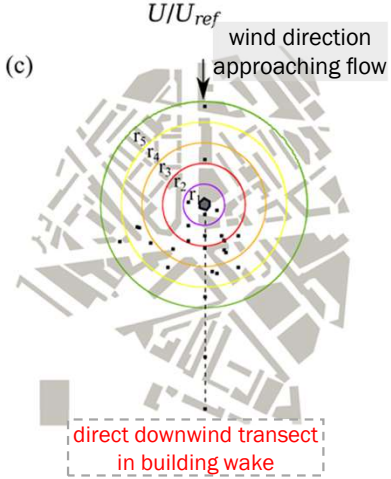

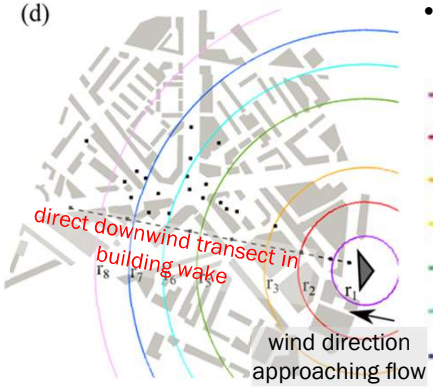

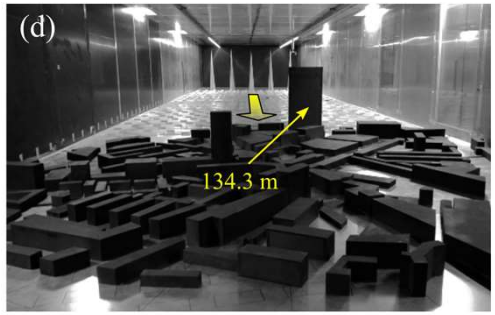

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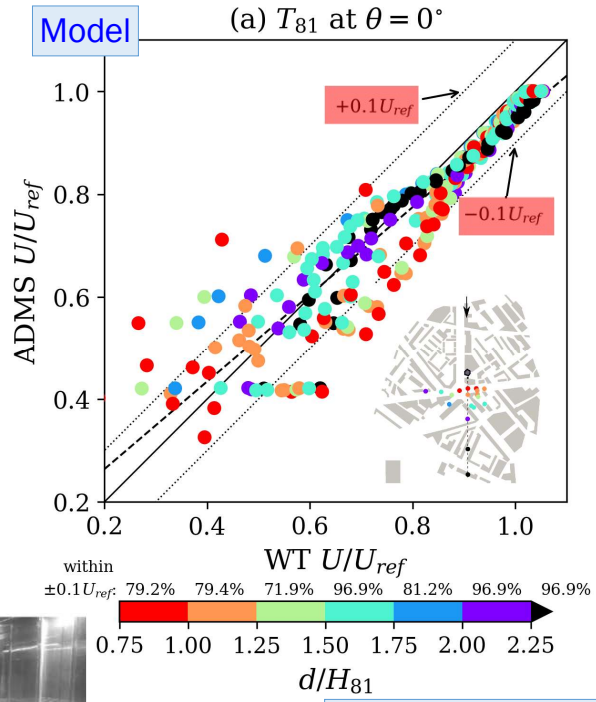
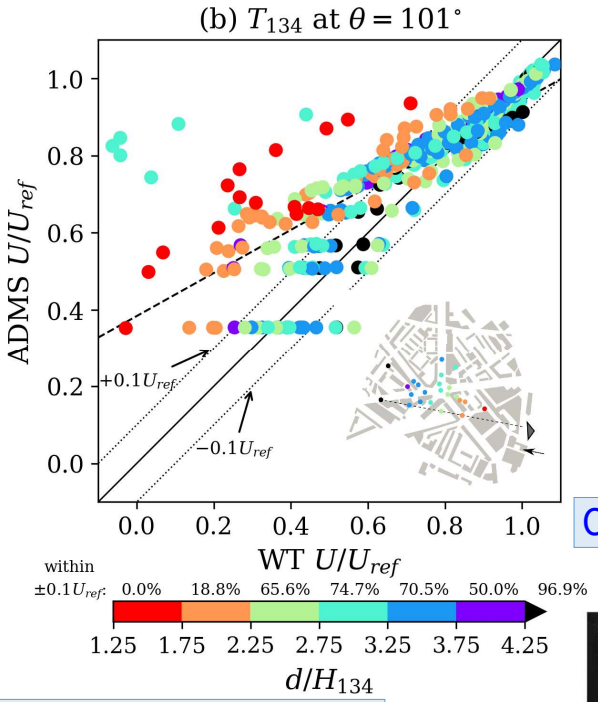
Hertwig *et al.* (2019) ***BLM*** https://doi.org/ 10.1007/s10546-019-00450-7

Hertwig et al. (2021) *Faraday Discussions* https://doi.org/10.1039/D0FD00098A

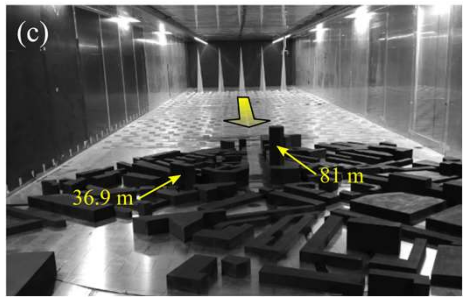
Along-wind velocity (U/U_{ref}) in the main wake behind Isolated Tall Buildings (TB)

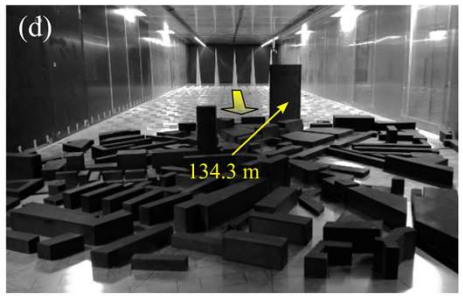
Model





Observations





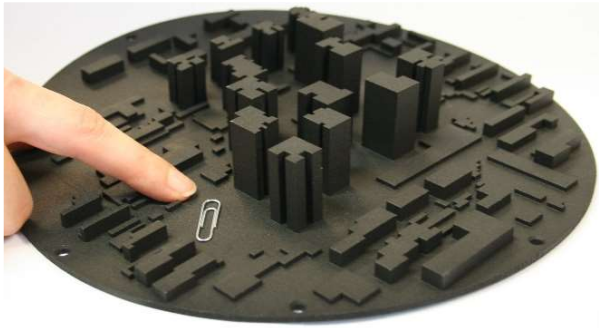
Straight-line distance (d/H_{TB}) from the centre of TB

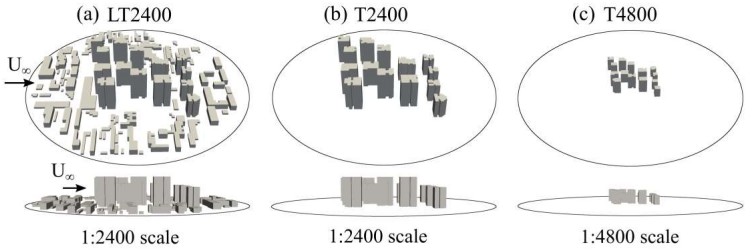
Each site has data pairs at several heights

Hertwig *et al*. (2019) *BLM* https://doi.org/ 10.1007/s10546-019-00450-7

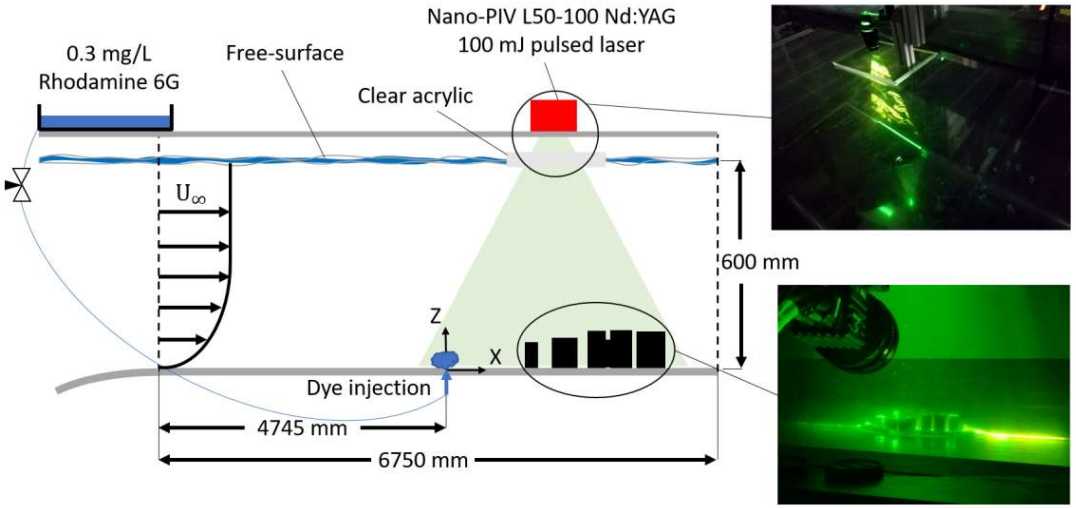
Hertwig et al. (2021) *Faraday Discussions* https://doi.org/10.1039/D0FD00098A

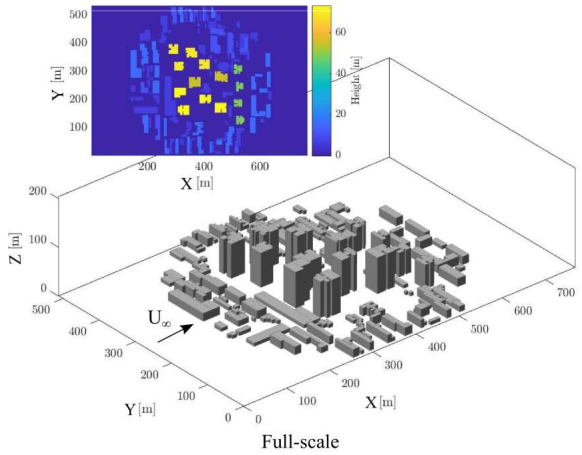
Univ. of Southampton Water flume setup: Cluster of Tall Buildings (Beijing)





Particle Image Velocimetry (PIV) and Planar Laser Induced Fluorescence (PLIF)





Hertwig et al. 2021 *Faraday Discussions* https://doi.org/10.1039/D0FD00098A
Lim et al. 2022: *Pollutant dispersion by tall buildings in rural-to-urban landscapes: Laboratory experiments and Large-Eddy Simulation*, Experiments in Fluids EXIF-D-21-00325

Cluster of Tall Buildings (Beijing)

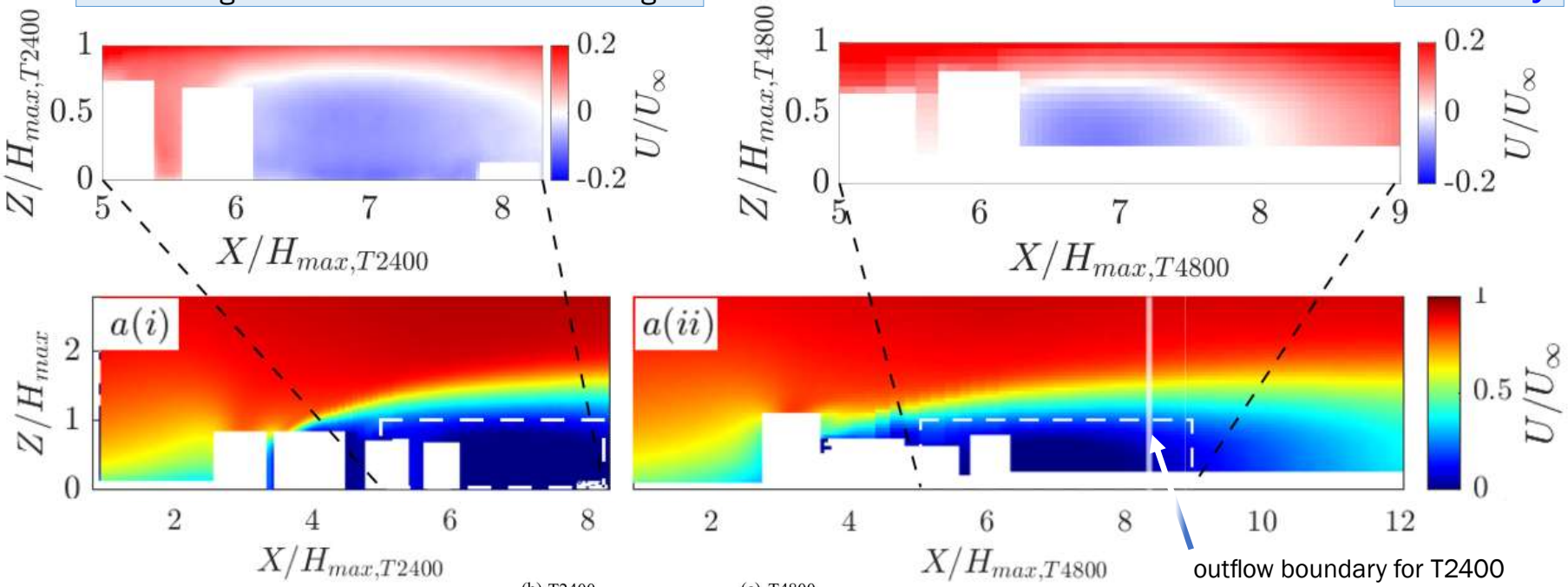
Mean velocity

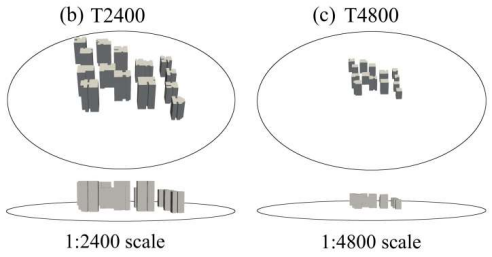
recirculating flow in the cluster near-wake region

UCL

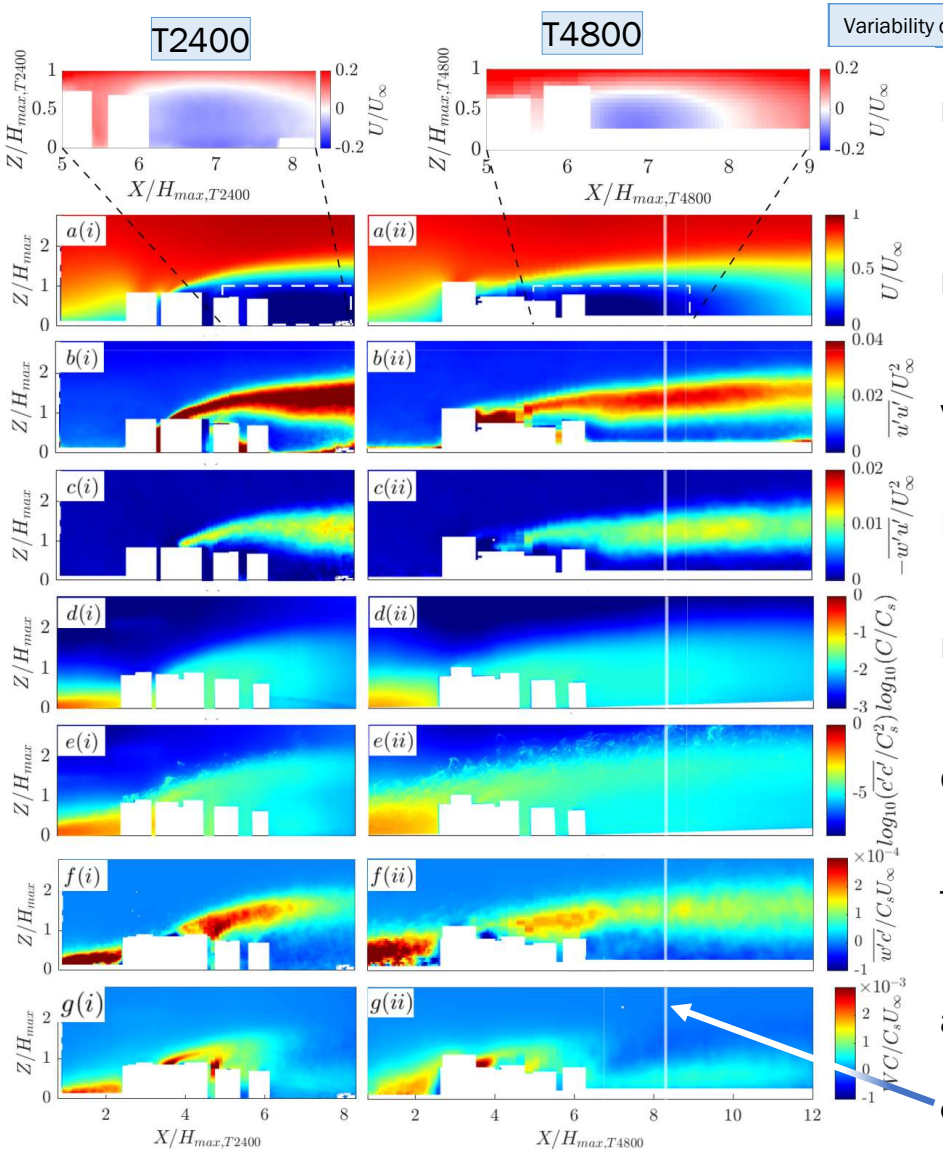
RSL

UCL





Lim et al. 2022:Experiments in Fluids EXIF-D-21-00325



recirculating flow in the cluster near-wake region

mean velocity

velocity variance

Reynolds shear stress

mean concentration

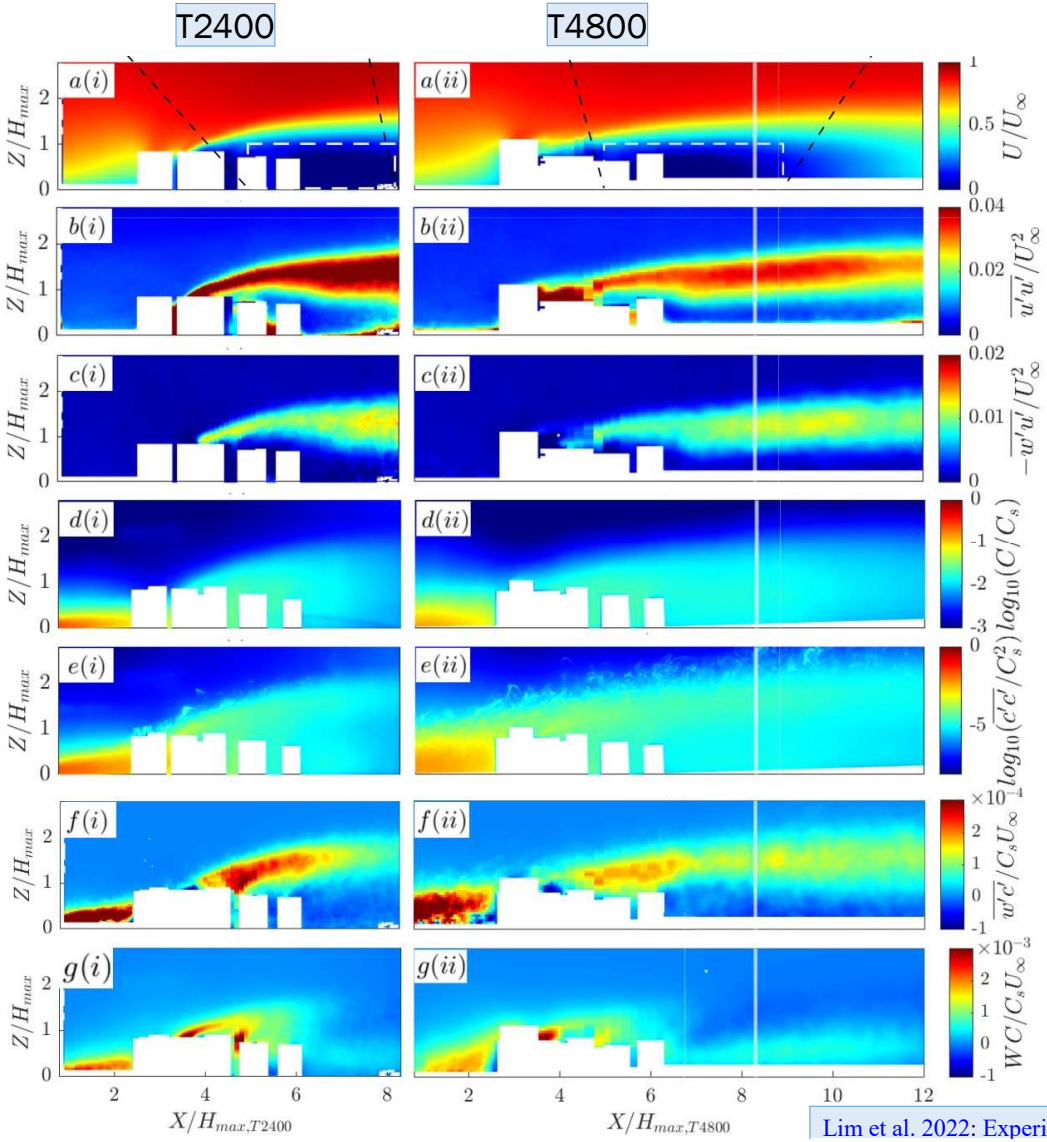
concentration variance

turbulent scalar flux

advective scalar flux

outflow boundary for T2400

Lim et al. 2022:Experiments in Fluids EXIF-D-21-00325



mean velocity

velocity variance

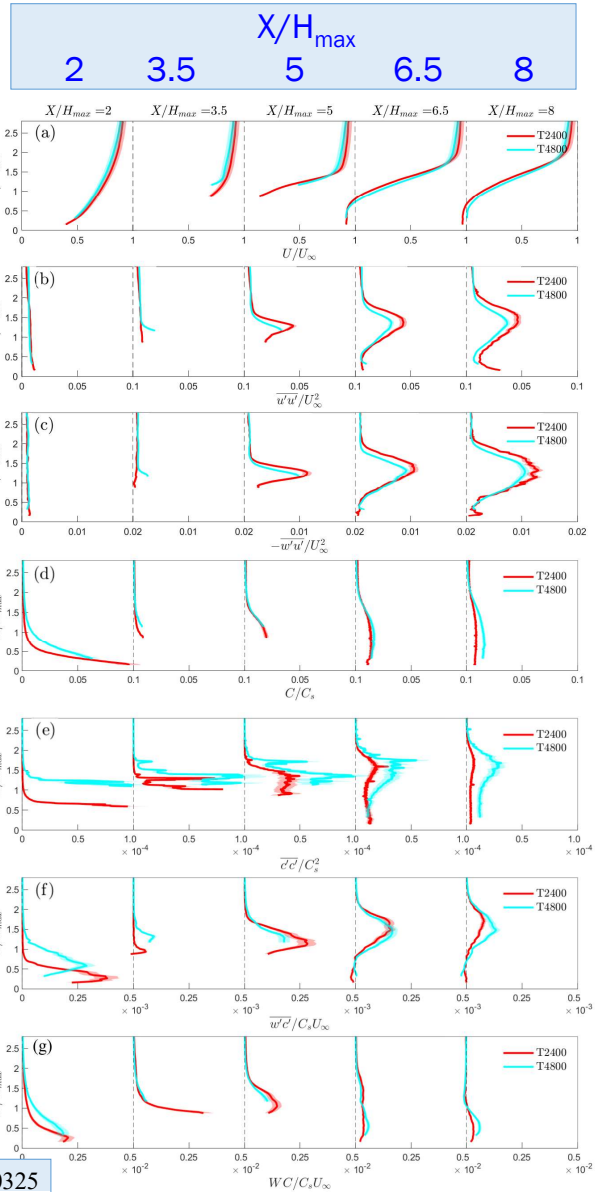
Reynolds shear stress

mean concentration

concentration variance

turbulent scalar flux

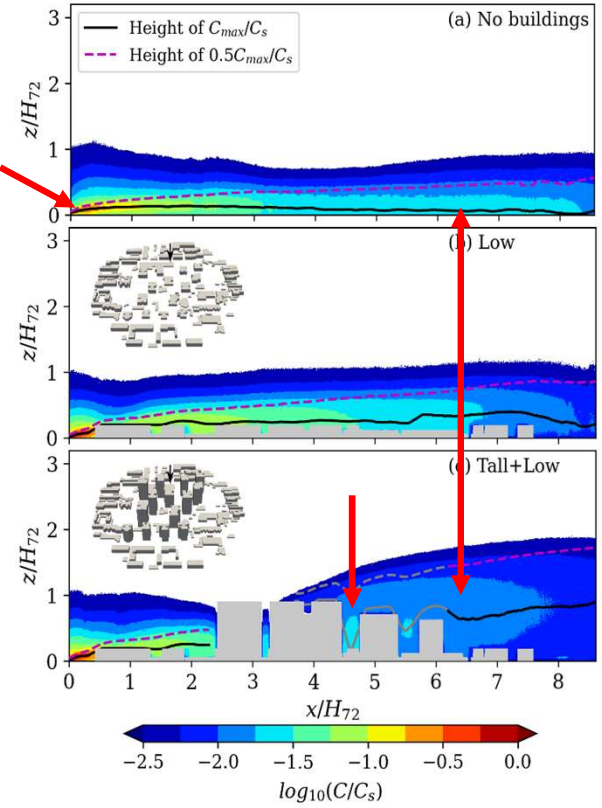
advective scalar flux

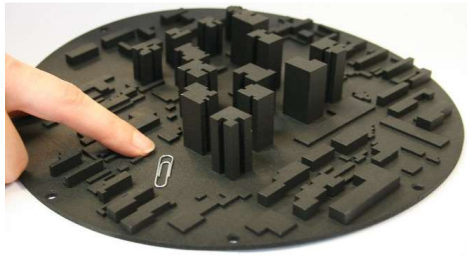


Lim et al. 2022: Experiments in Fluids EXIF-D-21-00325

Cluster of Tall Buildings: Beijing

Observations



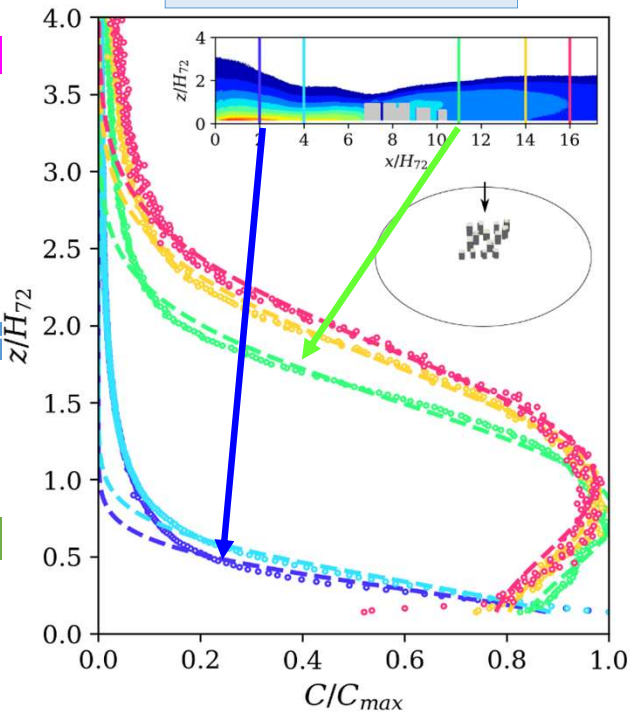


Inertial sublayer

Roughness sub layer

Urban canopy layer

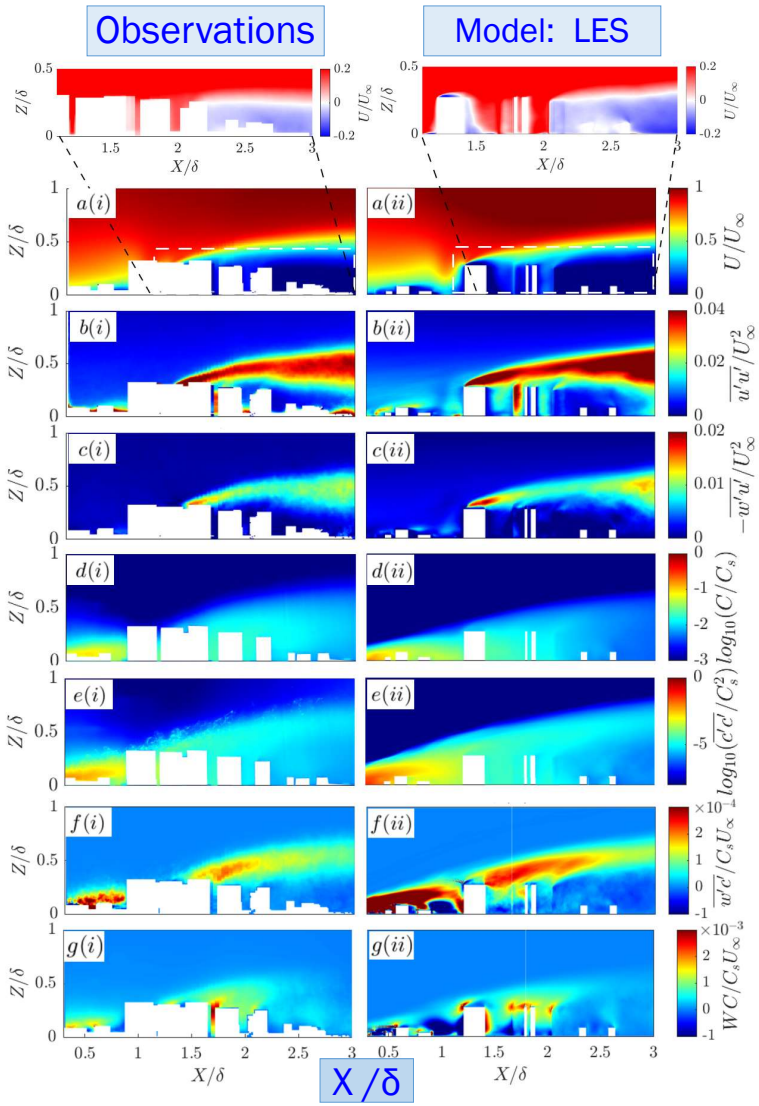
Modelling



Hertwig et al. 2021 *Faraday Discussions* https://doi.org/10.1039/D0FD00098A

Cluster of Buildings

Normalised by
Boundary layer depth



Lim et al. 2022: Experiments in Fluids EXIF-D-21-00325

mean velocity

velocity variance

Reynolds shear stress

mean concentration

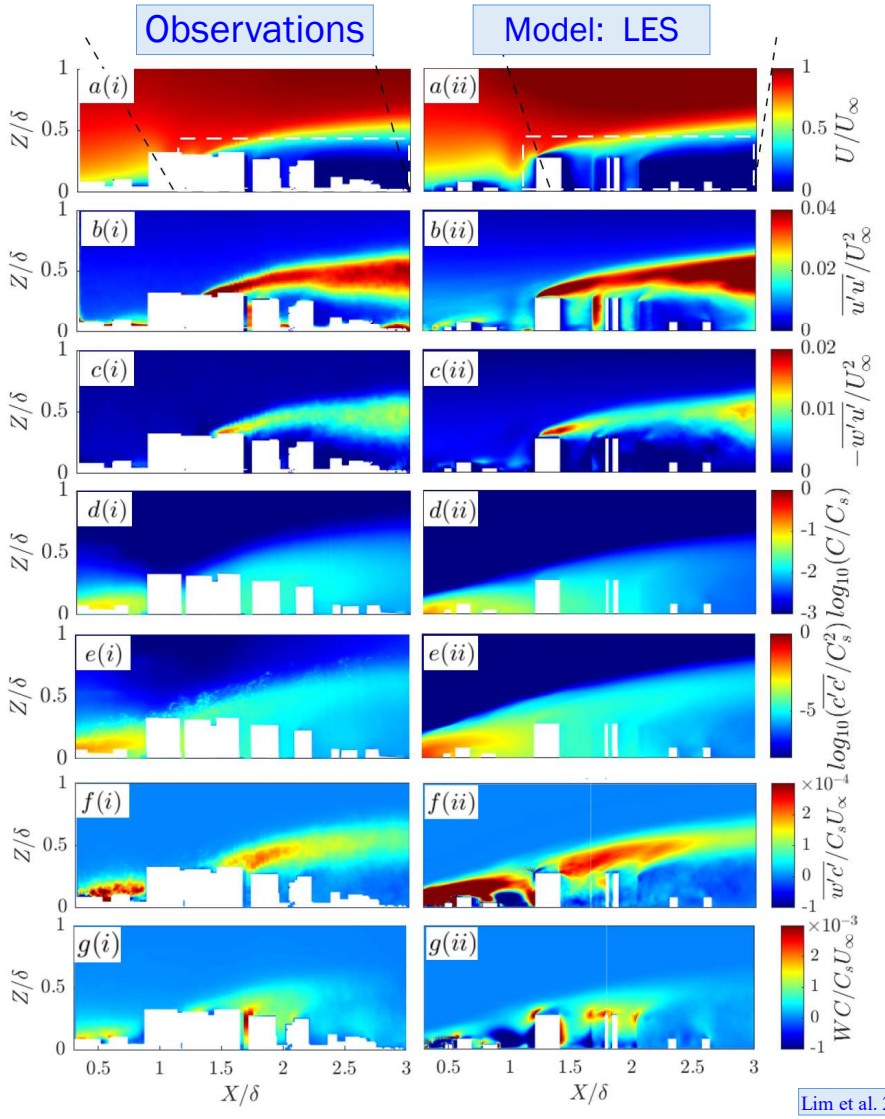
concentration variance

turbulent scalar flux

advective scalar flux

X streamwise distance
Z Height (vertical)
δ Boundary layer depth

Lim et al. 2022: Experiments in Fluids EXIF-D-21-00325



mean velocity

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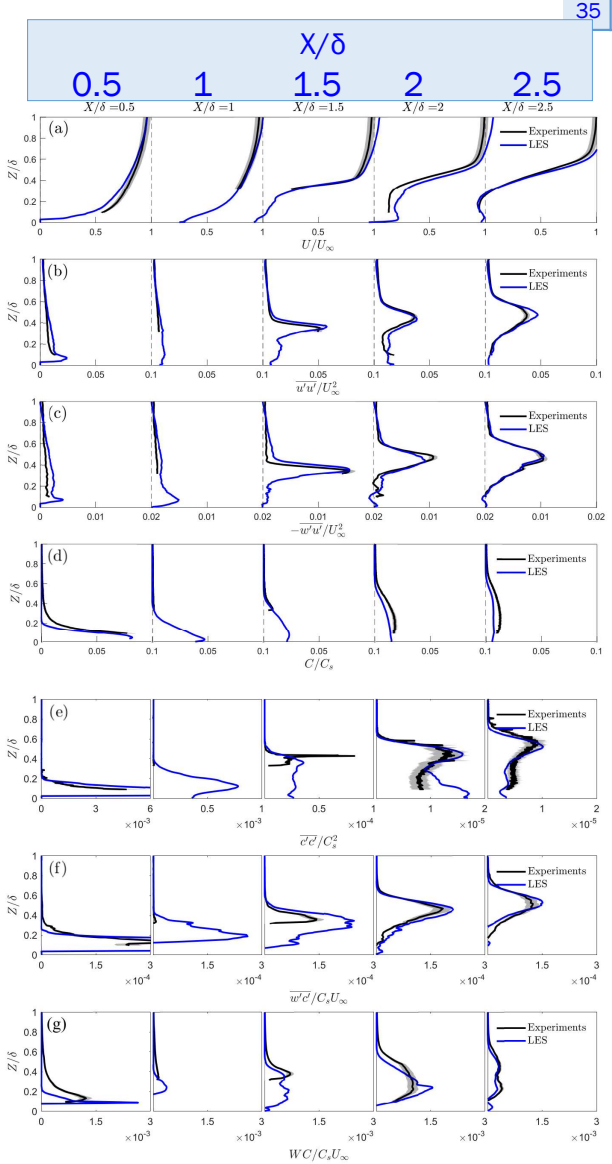
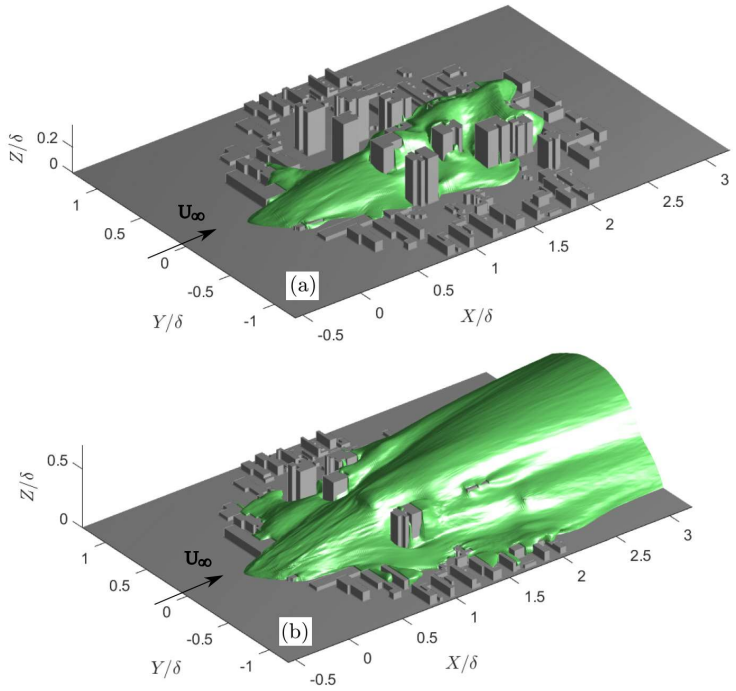


Lim et al. 2022:, Experiments in Fluids EXIF-D-21-00325

Isosurfaces of the concentration plume: LES



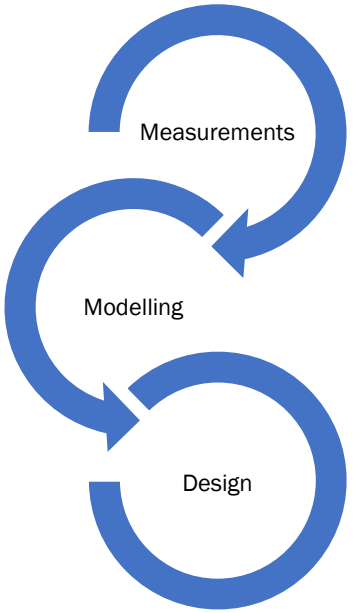
Isovalue: $C/C_B = 10^{-2}$

Isovalue: $C/C_B = 10^{-3}$

Lim et al. 2022:, Experiments in Fluids EXIF-D-21-00325

Final Comments

- We need to understand the impacts of physical meteorology to improve both observations and modelling



- As we obtain acceptable 'simple' models – we need to address more complex situations
  - Atmospheric conditions e.g. stability
  - Building morphology and materials e.g. not homogenous
  - Human activities e.g. timing and locations of emissions

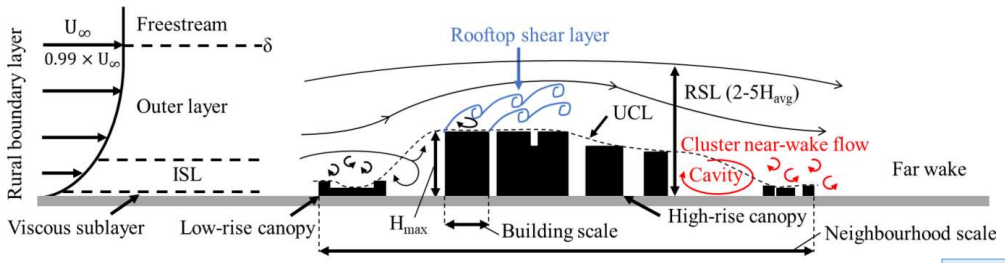
- A range of models are needed for a wide range of purposes

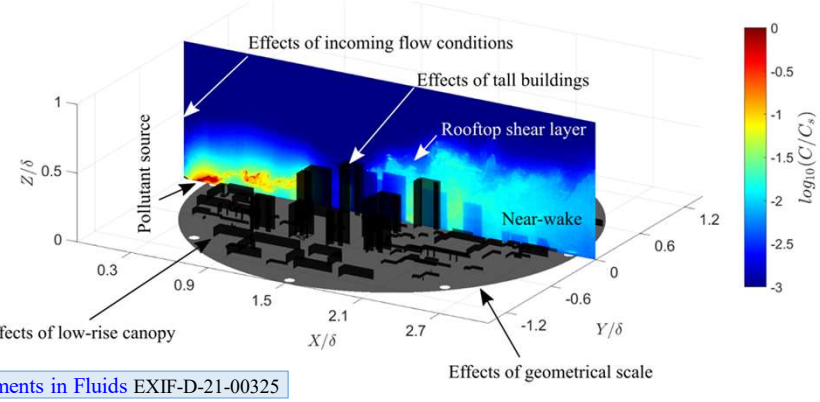
→ Improve weather or climate forecasts

→ Improve building design

→ Reduce unnecessary energy use, reduce CO_2 emissions

→ Improve CO_2 modelling in urban areas

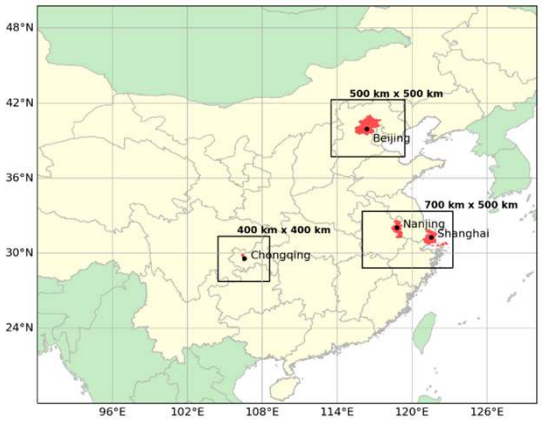




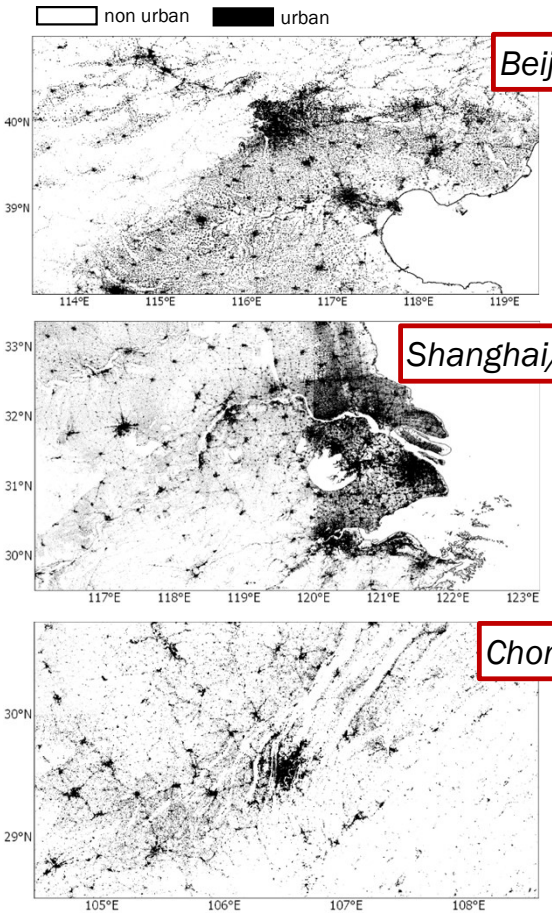
Lim et al. 2022:, Experiments in Fluids EXIF-D-21-00325

Land-cover ancillaries of the online HadGEM3 Best-1T simulations

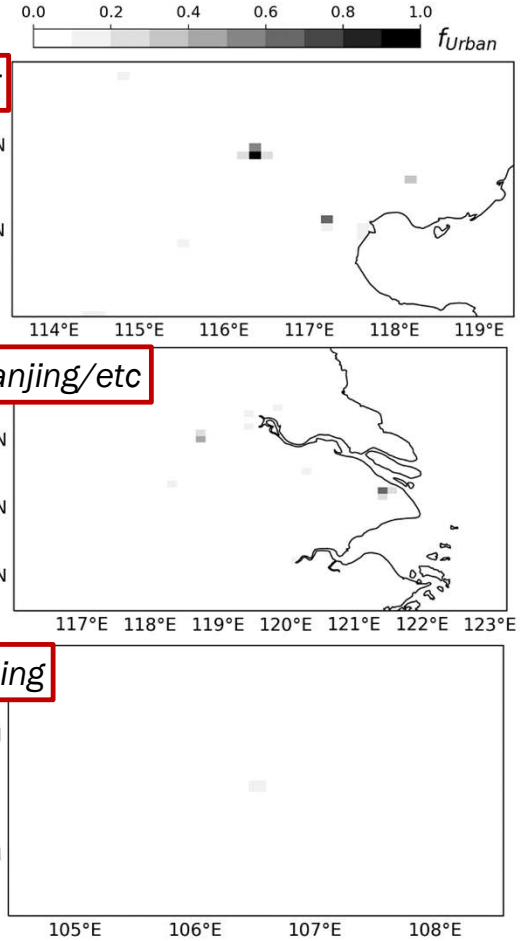
- **IGBP based LC over China**
  - Poor accuracy of urban fraction
  - used in HadGEM3 PRIMAVERA runs
- Better / more recent sources should be used



Binary Global Urban Footprint



IGBP urban land-cover fraction



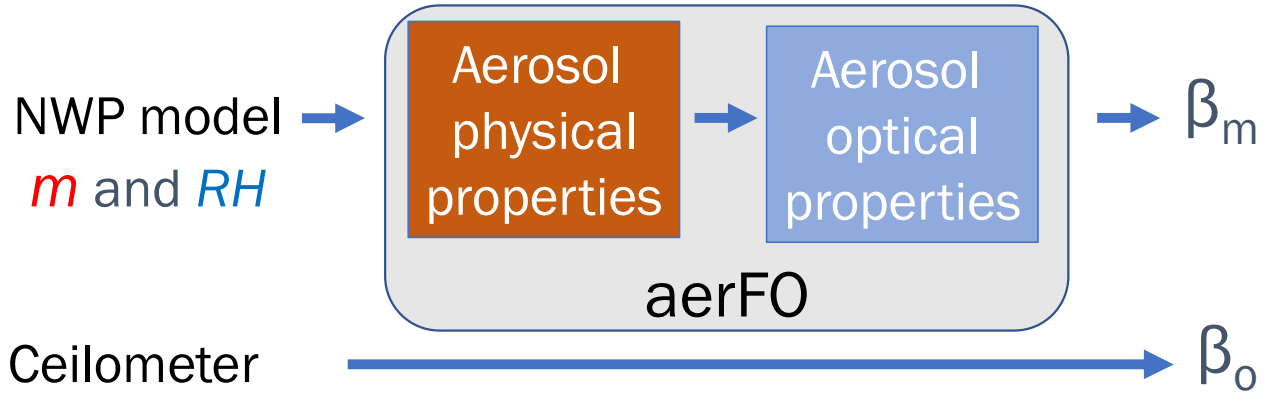
Hertwig et al. 2021: High-resolution global climate simulations: representation of cities. International Journal of Climatology 41, 3266-3285 https://doi.org/10.1002/joc.7018

Aerosol Forward Operator (aerFO): to estimate attenuated backscatter (β_m)

- **Data assimilation** – needs to be computationally cheap

Lidar ratio = 60 sr	Aerosols
Ammonium Nitrate	NH_4NO_3
Ammonium Sulphate	$(NH_4)_2SO_4$
Aged Fossil Fuel Organic Carbon	OC

- Features:
  - Non-cloud conditions
  - Cites (AQ)
  - Wavelength dependent
  - Effect of hygroscopic growth on physical & optical properties via an extinction enhancement factor ($f_{RH,ext}$)
    - Includes effect of water vapour absorption



Warren et al. (2018) Atmos. Env.

Warren et al. (2020) AE (improved chemistry)

Fluxes: EC - long term measurements

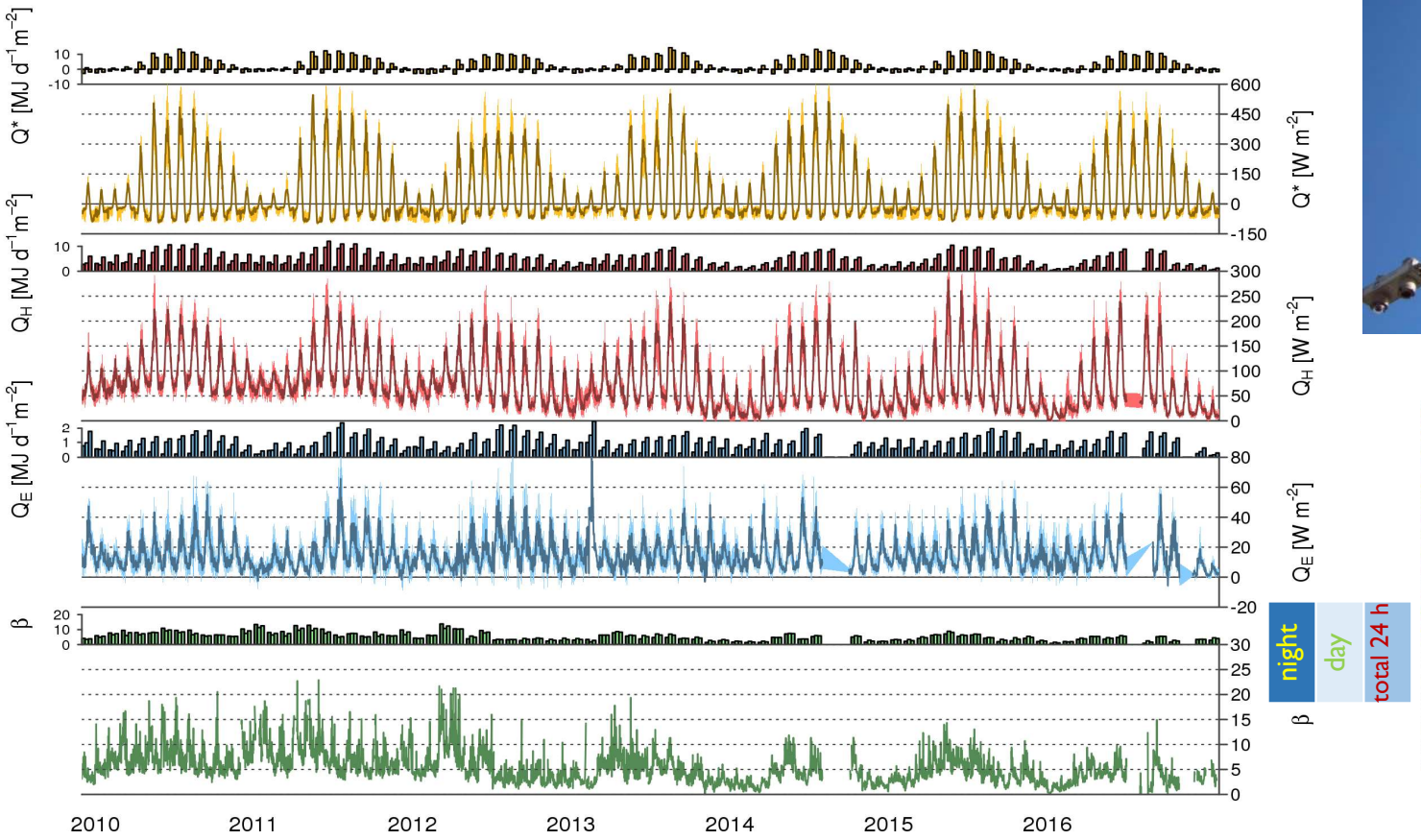
Monthly Median Diurnal Cycle, shaded IQR, KSS

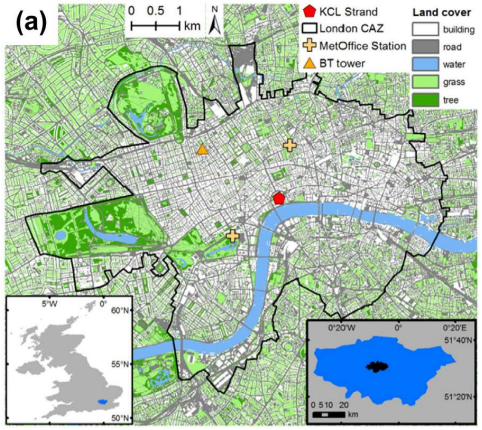
Q*

Q_H

Q_E

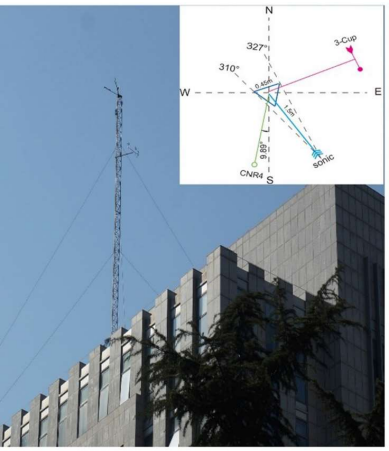
β

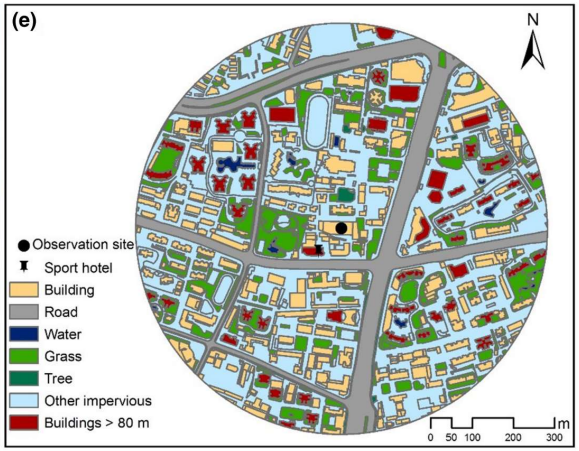




Kotthaus & Grimmond (2014a) Urban Climate, Kotthaus and Grimmond (in prep).

Challenges: Siting, Tall buildings





Ao et al. 2016 *Int. J. Climatol.* 36: 10.1002/**joc**.4657