Symons Gold Medal Lecture
RMetS 8 June 2022

Modelling urban-atmosphere exchanges: trade-offs between simplicity and complexity

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Thank the following people

- Oke Kotthaus Ward Sun Lindberg Järvi Offerle Hertwig Morrison Best Loridan Kent Crawford Warren Gabey Meyer Lipson Luo Omidvar Bjorkegren Capel-Timms Allen Wolfe Young Barlow Christen Martilli Masson Miao Mills Schmid Souch Voogt Baklanov Chen Cleugh Fortuniak Tan Li Halios Shi Chrysoulakis Evans Gough Lean Nemitz Oleson Squires Xu Bohnenstengel Liu Lee Cai Coe Fu Hu Jones Pigeon Randolph Theeuwes Wu Ao Blackett Hubble Gouvea Zutter Belcher Bloss Chang Chapman Dou Gao Gastellu-Etchegorry Gatey Hamilton Han Heard Huang King Lemonsu Muller Oliphant Ren Roth Salmond Steeneveld Su Tang Whalley Wild Yang Allan Carmichael Charlton-Perez Clark Cropley Dabberdt Eliasson Feigenwinter Grossman-Clarke Harrison Helfter Hendry Hewitt Hopkins Langford Ma Marconcini Mitraka Ni Olofson Ouyang Porson Roberts Schluenzen Slater Smith Sokhi Tombrou van Reeuwijk Vogt Wayson Xie Yin Yu Acton Bacak Baik Ballard Bannan Beddows Bornstein Bouchet Calmet Carruthers Ching Crilley Dandou Demuzere Ding Doherty Dragoni Duan Dunmore Edwards Ehman Feddema Ge Golding Grant Haeffelin Hamdi Hanna Hanson Heisler Holmer Holtslag Hong James Jonsson Kanda Kawai Kelly Kokkonen Kondo Kramer Krayenhoff Landier Lewis Liang Lin McFadden Michael Ng Norford Parlow Pawlak Percival Reeves Robins Salamanca Spano Tewari WMO Wood Zhang Arnfield Band Baumgardner Bellucco Betts Biggart Black Bonnefond Boutle Bruse Cadenasso Cao Carroll Cheng Coceal Cui Dousset Durand Dye Emmanuel Esch Fallmann Falloon Famulari Feng Flynn Freer-Smith Froelich Green Grove Hara Harman He Heal Hogan Hollaway Hovespyan Hoxey Iamarino Irvine Jenkins Joe Kawamoto Kikegawa Klostermann Kłysik Kropp Kusaka Lagouarde Lauret Lawrence Long Lu Magliulo Malamud Manning Marras McFiggans McGuire Mehra Mestayer Middleton Niyogi Noakes Nowak O'Connor Onomura Pain Parrish Pickett Potter Quinn Rickard Rooney Rotach Ryu Sailor Schoetter Scott Setälä Shao Shaw Stagakis Staszewski Stocker Strachan Synnefa Taka Takane Toscano Tremper Tsiringakis Vanderwel Velasco Vidale Vogel Wang Woodward-Massey Wooster Worrall Xing Xiong Yao Ye Yue Zheng Zilitinkevich + Many others

- Undergraduates and Graduates students at IUB, KCL and UoR – who have participated in fieldwork
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- Family (near and far)

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- **NERC ASSURE**: Across-Scale processeS in URban Environments; **ERC** Synergy Grant ***urbisphere*** - coupling dynamic cities and climate; **EPSRC** Fluid dynamics of Urban Tall-building clUsters for Resilient built Environments (**FUTURE**), **NERC APEx**: An Air Pollution Exposure model to integrate protection of vulnerable groups into the UK Clean Air Programme; **NERC** Climate service for resilience to overheating risk in Colombo, Sri Lanka: a multi-scale mapping approach (**COSMA**)

- MO Strategic Priorities Fund Climate Resilience Programme – 100m-scale Modelling for Urban Climate Services: Urban Climate Services using 100 m Resolution modelling, Newton Fund/MO CSSP China Next Generation Cities; Newton Fund/MO WCSSP HighResCity; Newton Fund/MO WCSSP End User Needs for City Based Climate Services in China; ViewPoint, MO Case stu

- PhD Studentships: NERC Case, EPSRC, MO Case, UoR, NERC SCENARIO, ERC, NSF, KCL, IUB

- UK Global Challenge Research Fund GCRF Urban Disaster Risk Hub, **EPSRC** Data Assimilation for the REsilient City (**DARE**); **NERC** An integrated study of air pollution processes in Beijing (**AirPro**); ECMWF Copernicus Services; **EPSRC** Low carbon climate-responsive Heating and Cooling of Cities (**LoHCool**); Royal Society-Newton Mobility Grant; MO/LCCP/Lloyds of London Environmental observations requirement for London; NERC ClearfLo, NERC/CEH, EUf7 emBRACE, EUf7 BRIDGE, NERC/ARSF, Met Office, US NSF, USDA Forest Service, EUf7 MegaPoli, NERC/ARSF, KCL, University of Reading, NERC TRUC, H2020 UrbanFluxes, Euf7 MegaPoli, NERC HiTemp, SCE, DTRA, NATO, US DoE etc

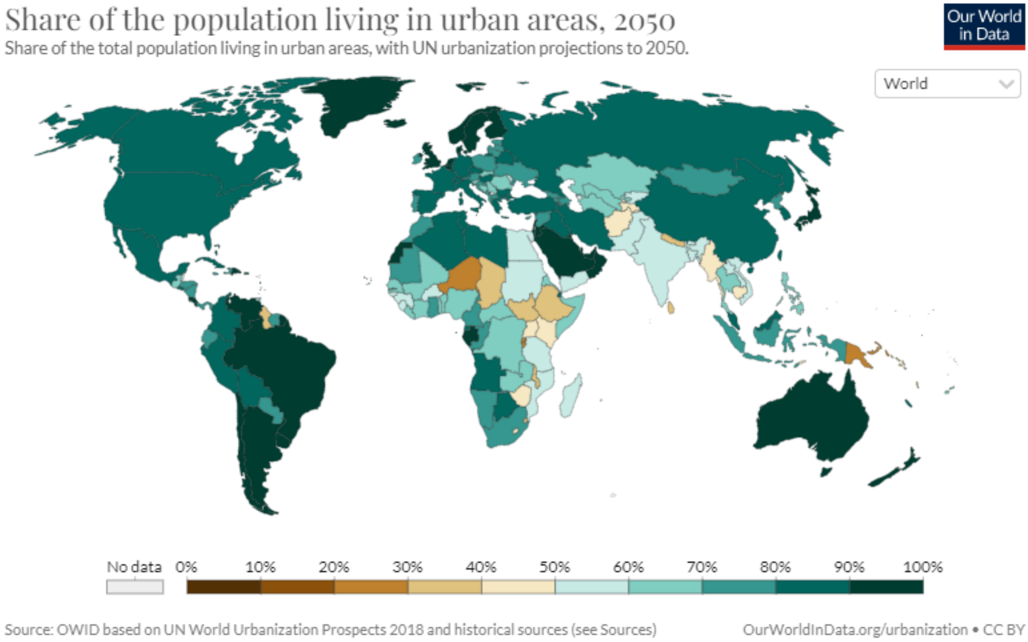
- *Facilities*: UKRI University of Southampton Water Channel, NERC University of Surrey EnFlo Wind tunnel, EPSRC MAGIC London hardware model, Site providers

Change: Importance of Urban Climates

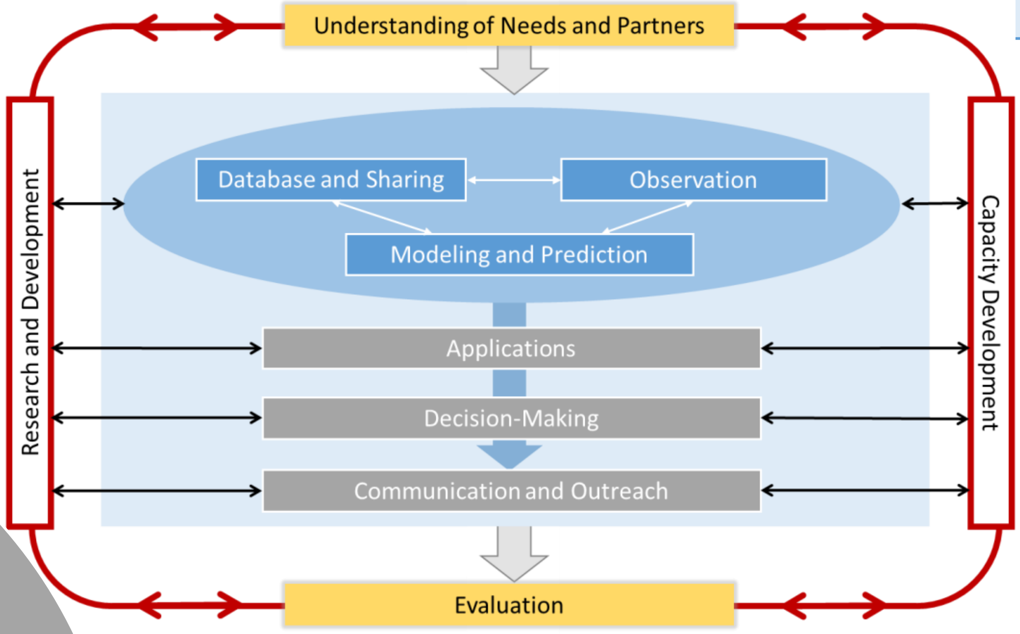
Climate Services
- Integrated urban services

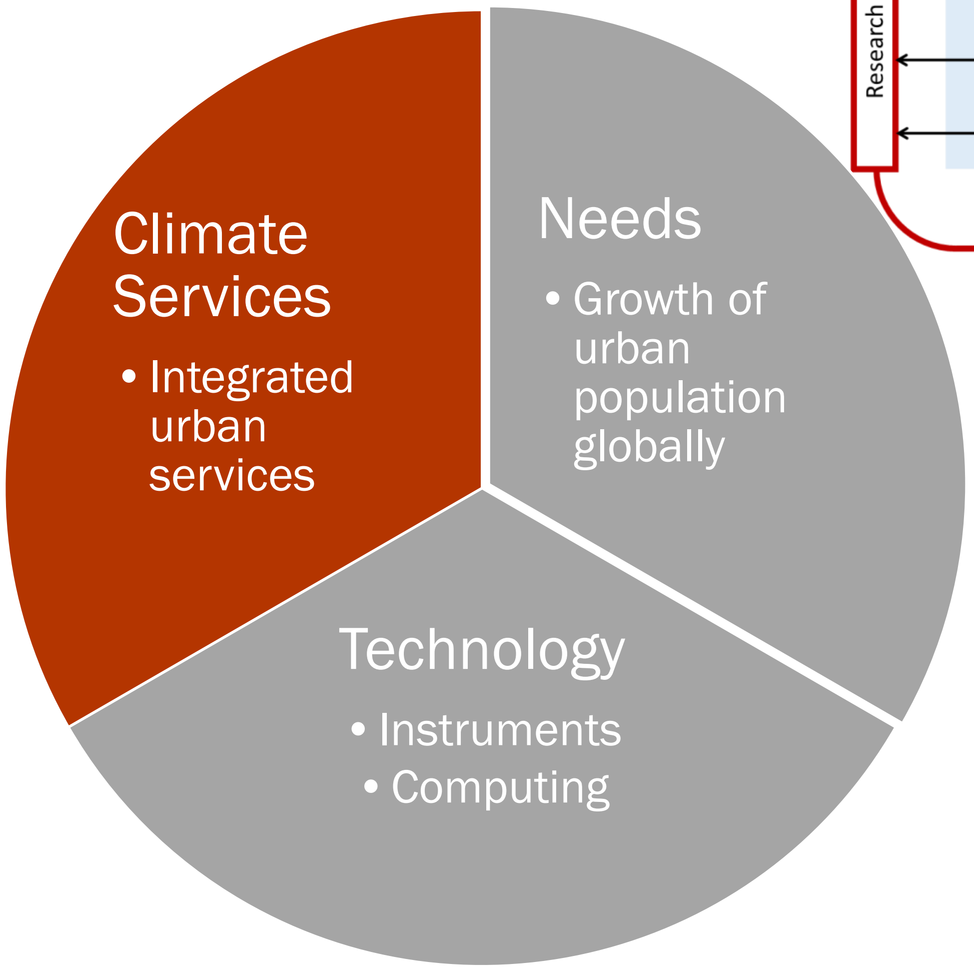
Needs
- Growth of urban population globally

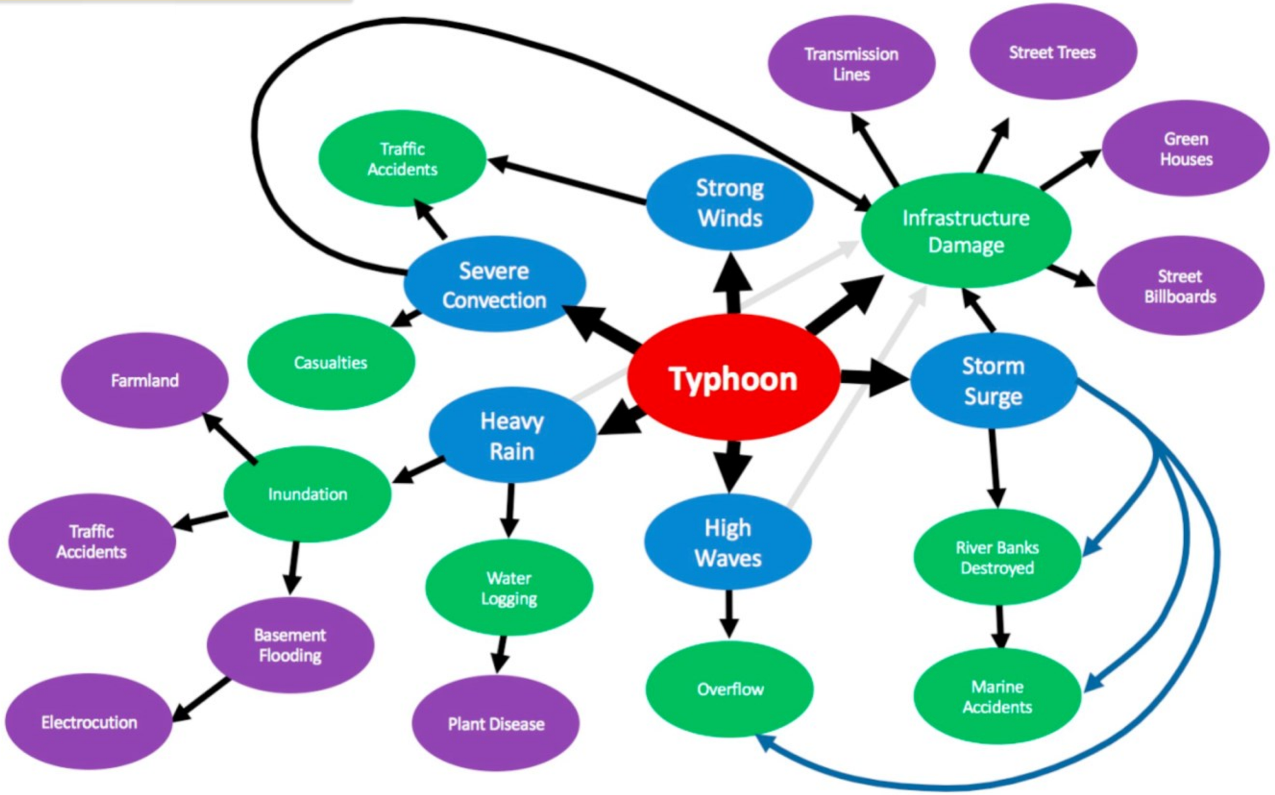
Technology
- Instruments
- Computing



Change:
Forecast to Services







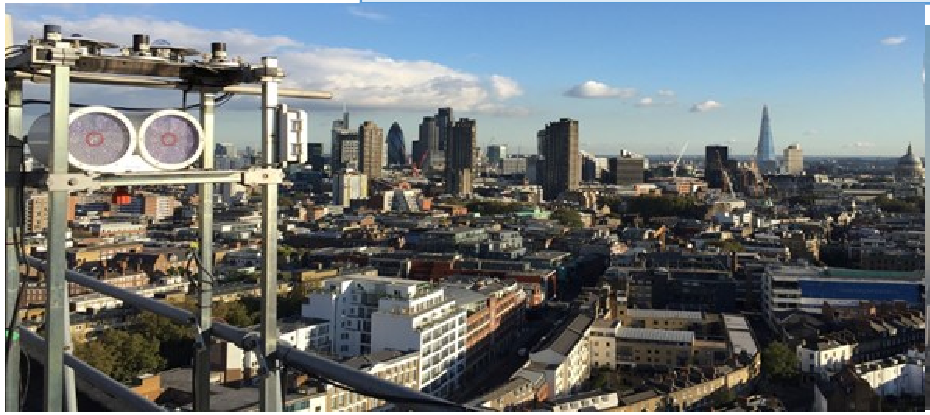
Grimmond et al. 2020 Urban Climate

WMO (2019) Guidance on IUS : Volume I: Concept and Methodology

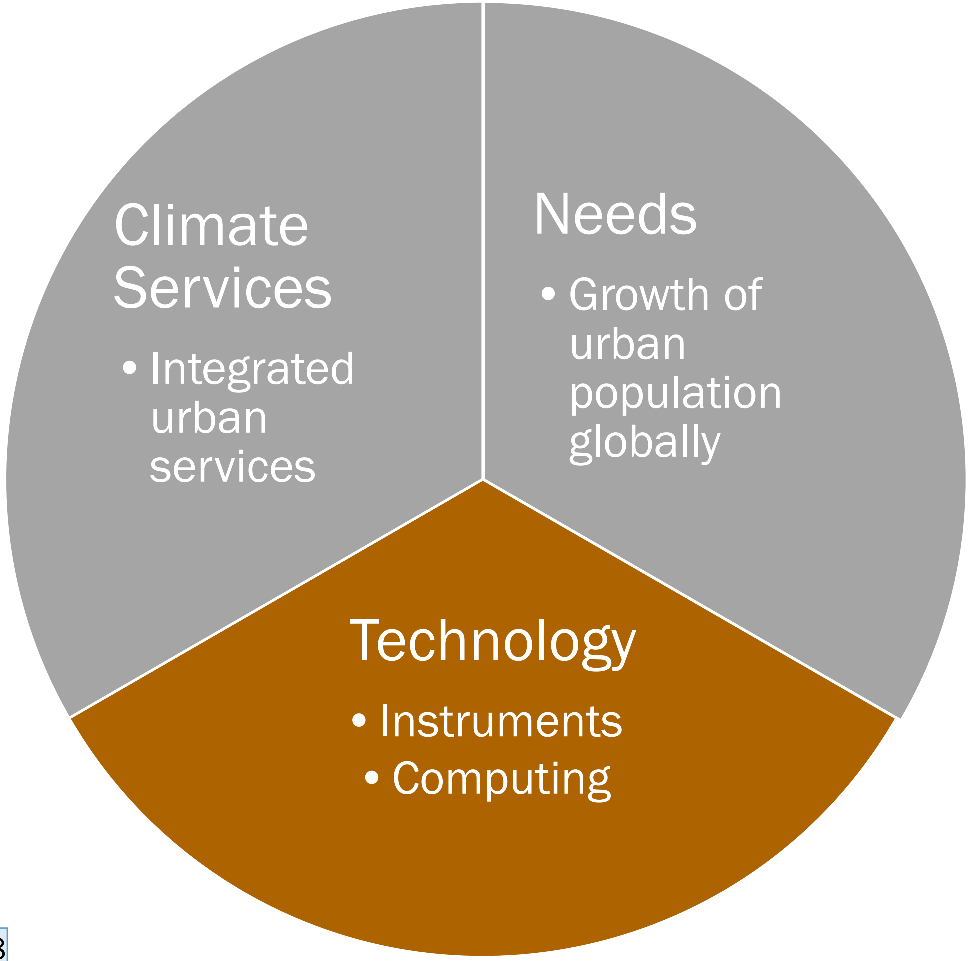
FIG. 5. The yaw sphere-thermometer system.

Yap, Black, Oke 1974 JAM)

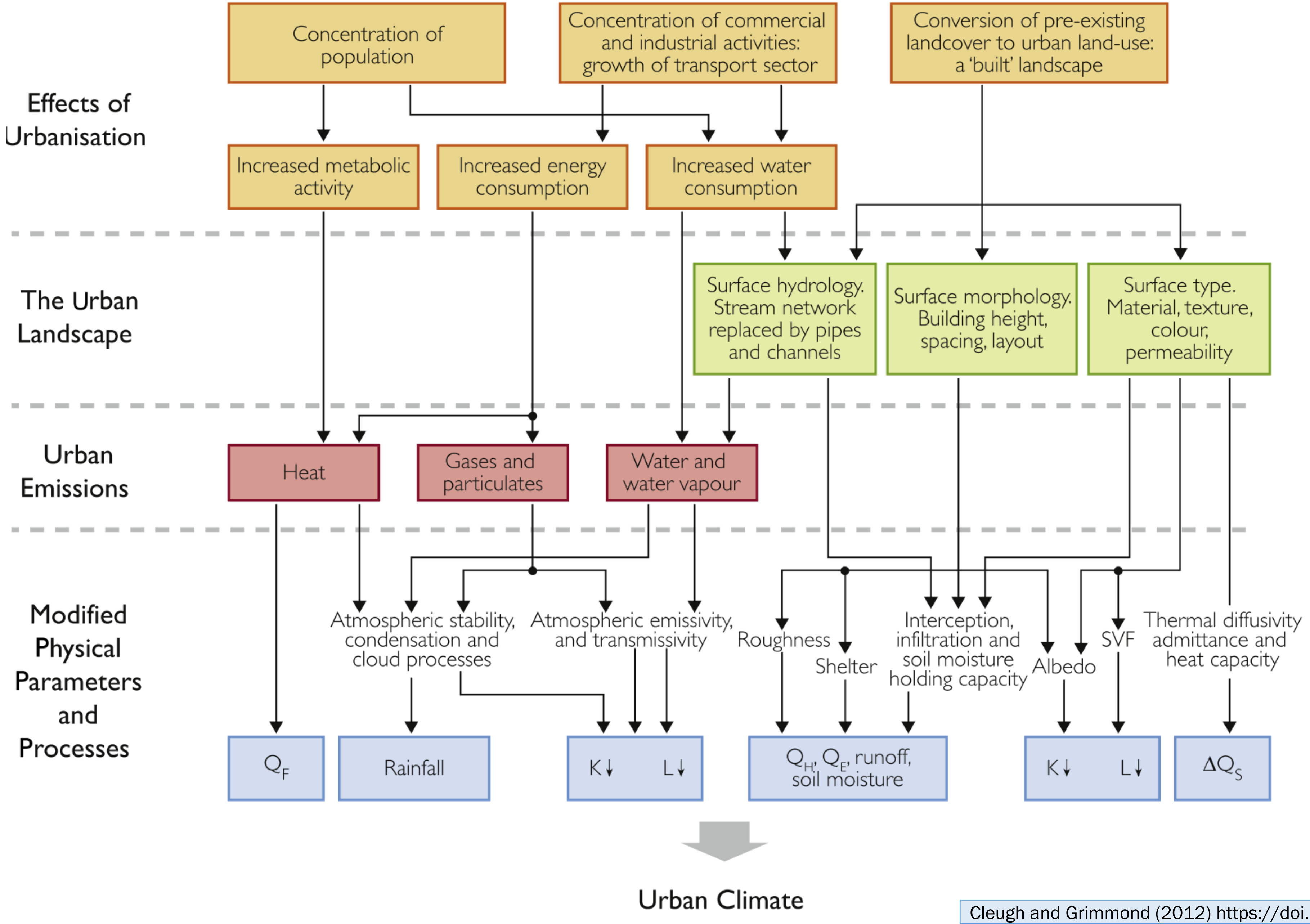
Grimmond 1988



Change



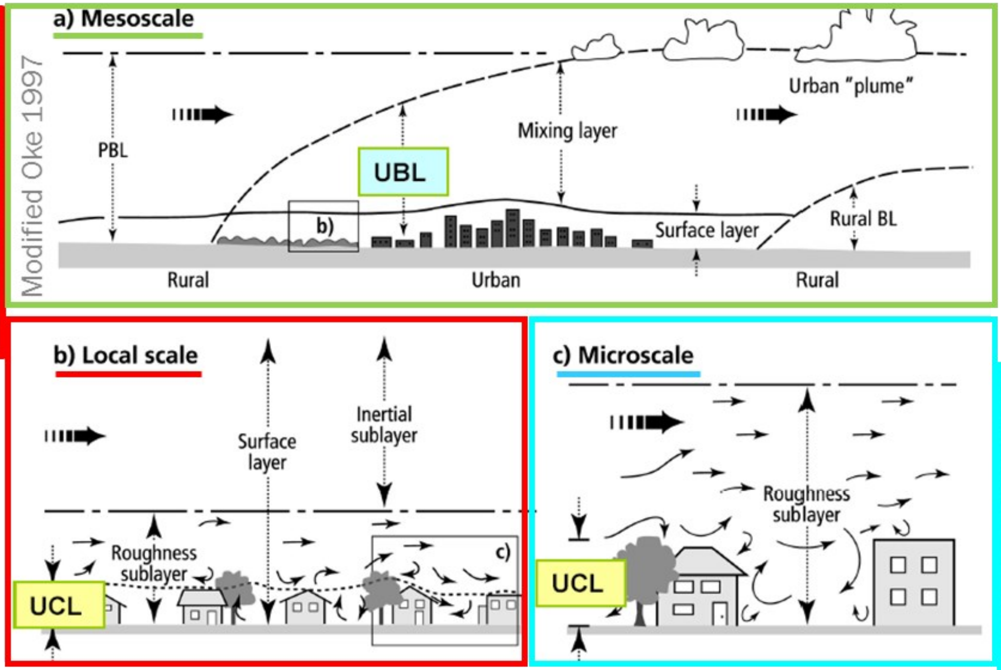
Urban Atmospheric Processes



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

Challenge of scale

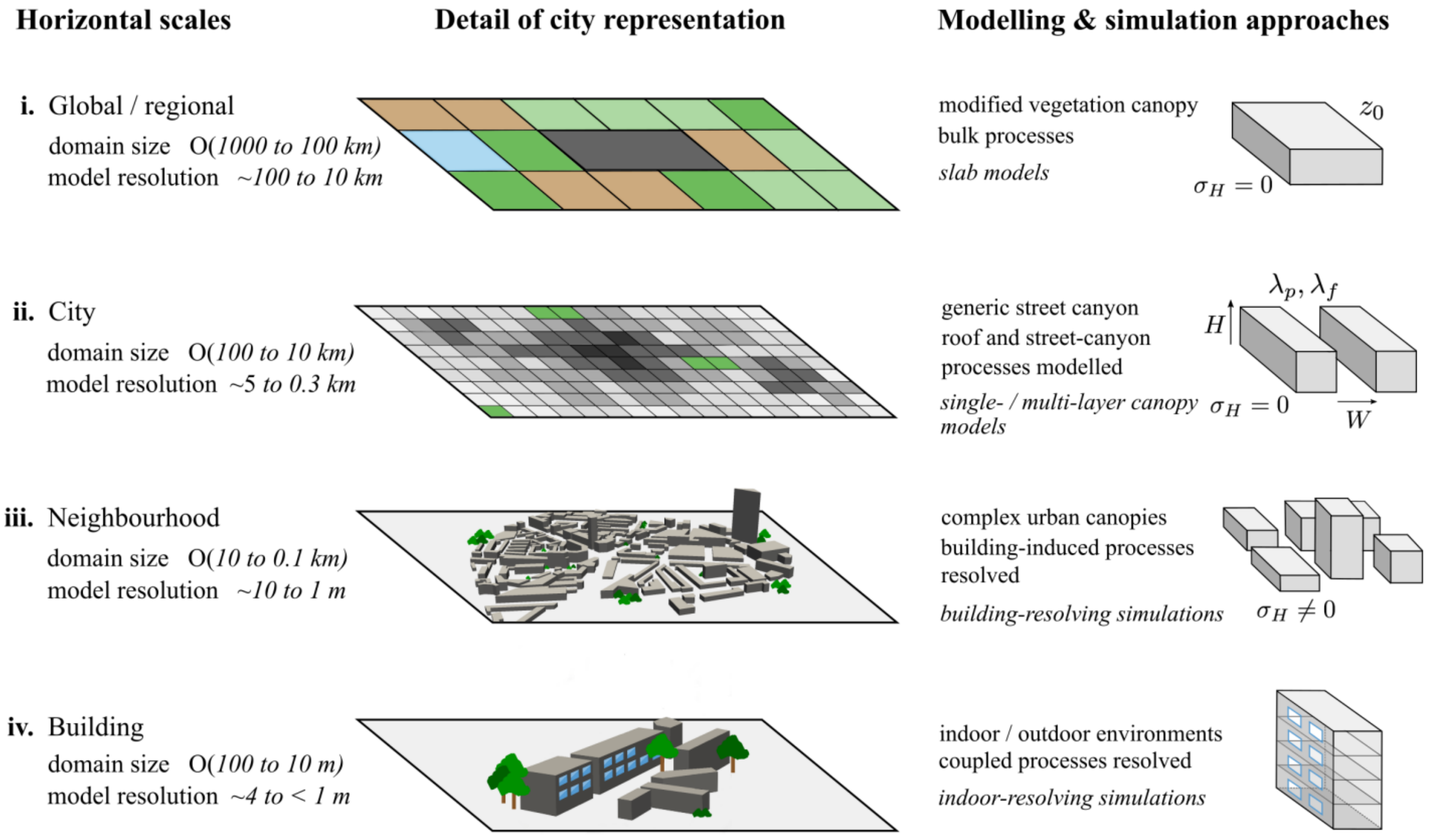
- Observe over relatively small areas
- Need to model (NWP, Climate, Applications) for complete city (and region) at an appropriate scale

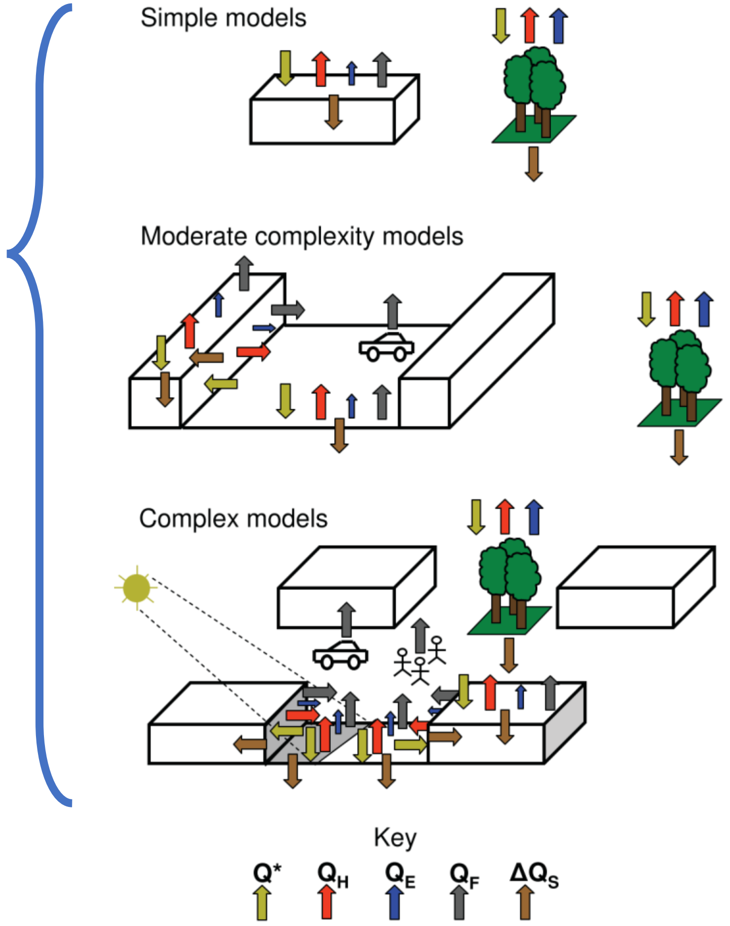



Gothenburg


Chicago

Modelling: Climate, Weather, Planning, Building Design



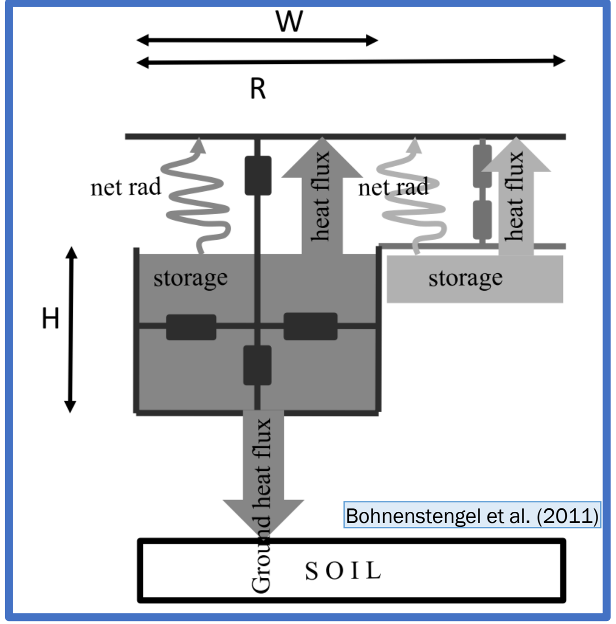


Hertwig et al. (2021) https://doi.org/10.1002/joc.7018

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

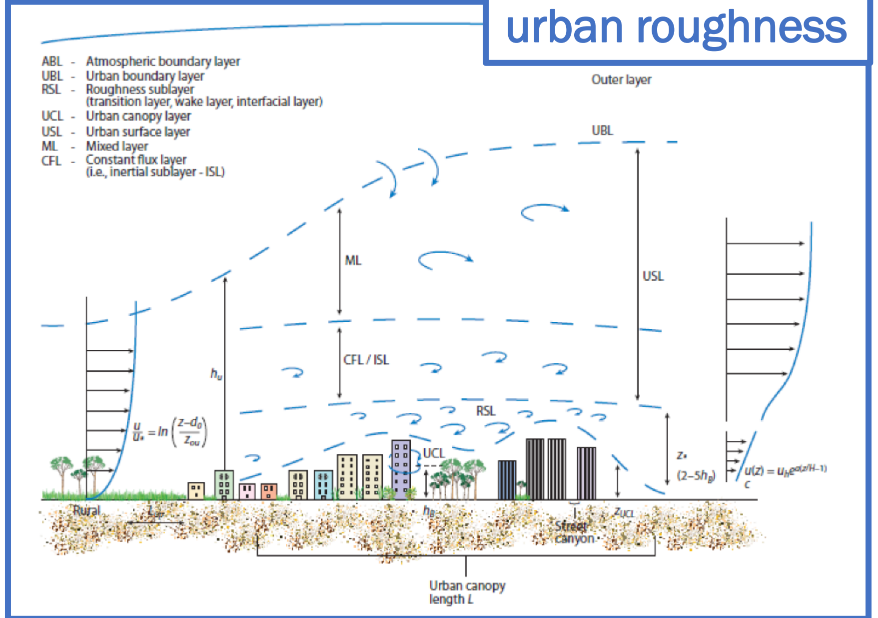
Urban Characteristics

urban morphology

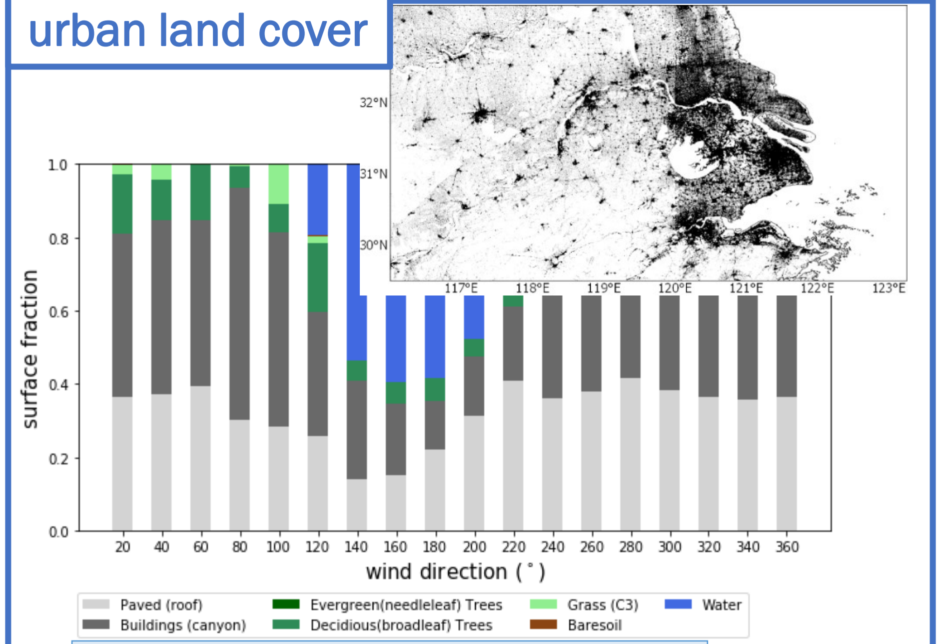


Bohnenstengel et al. (2011)

urban roughness



urban land cover



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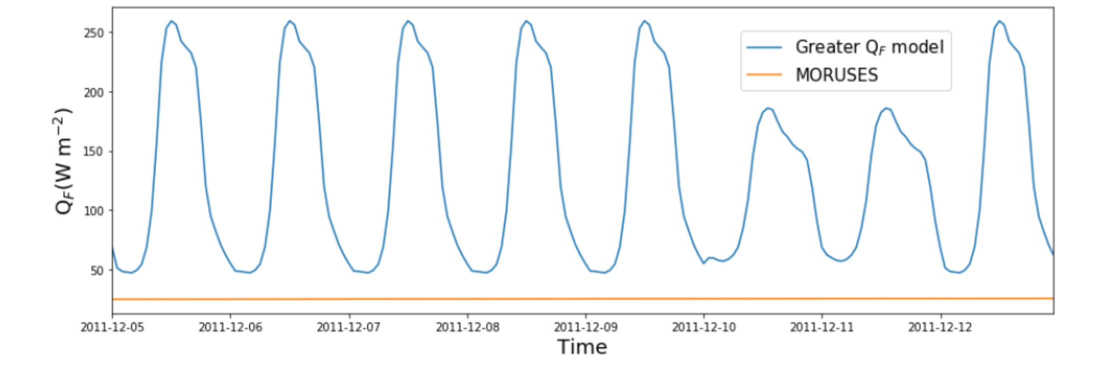
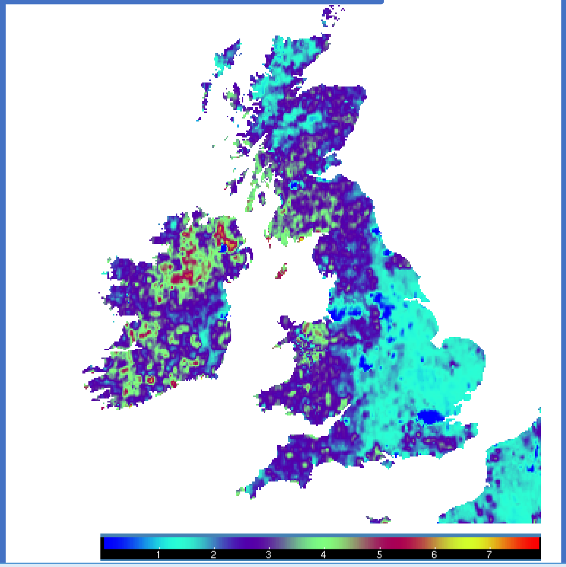
anthropogenic heat

Treated as parameter- should be dynamic

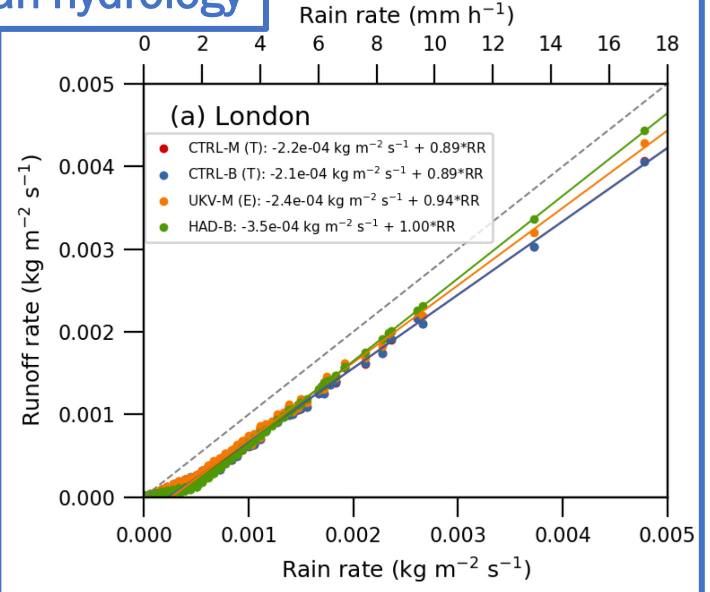


urban phenology



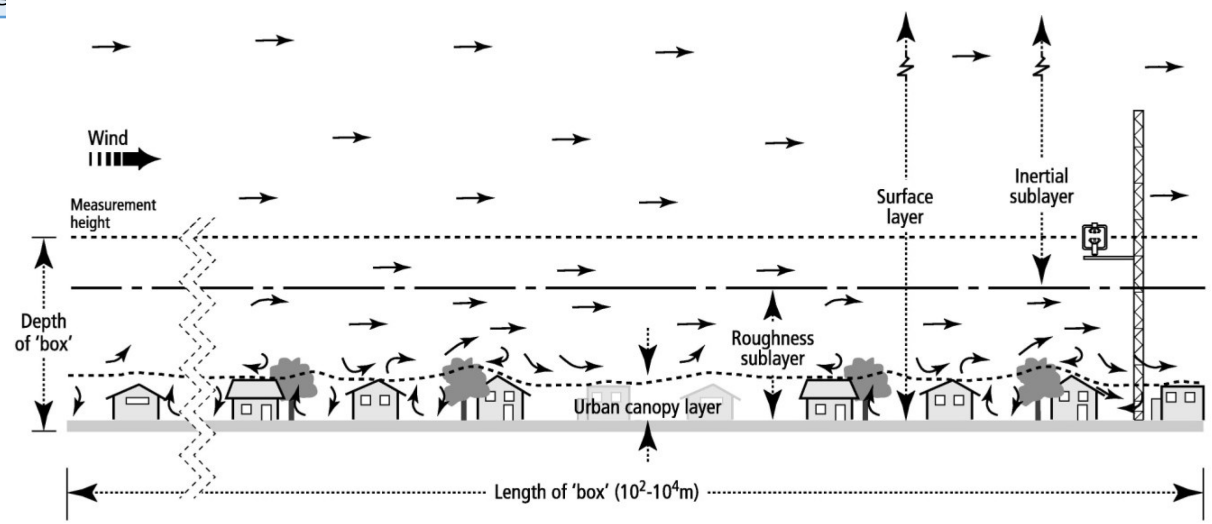
Hertwig et al. (2021) *TAAC* https://doi.org/10.1007/s00704-020-03294-1

urban hydrology



Local Scale

Measurement Height

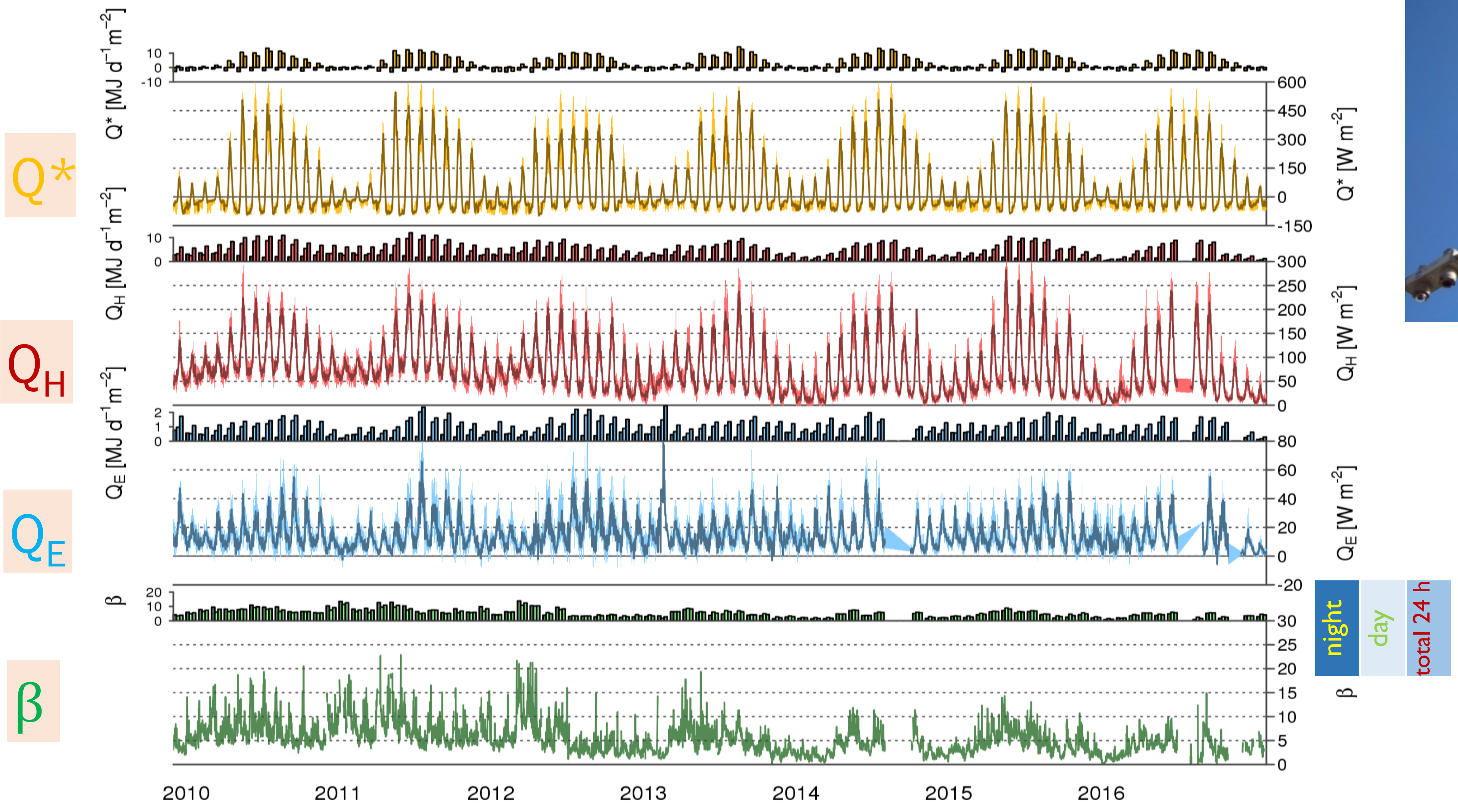


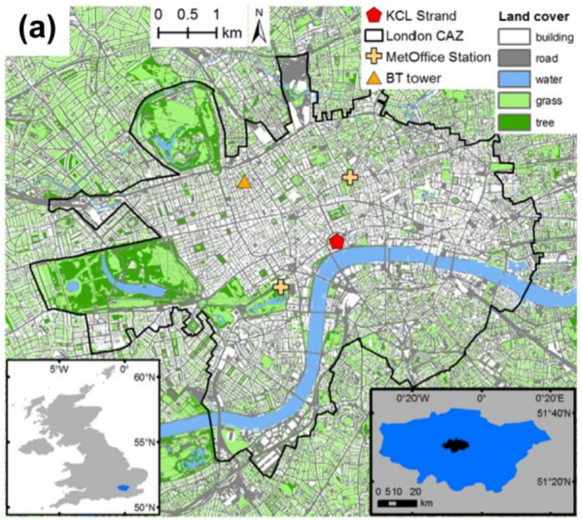
Grimmond and Oke 2002 JAM

http://www.bing.com/maps/

Fluxes: EC - long term measurements

Monthly Median Diurnal Cycle, shaded IQR, KSS



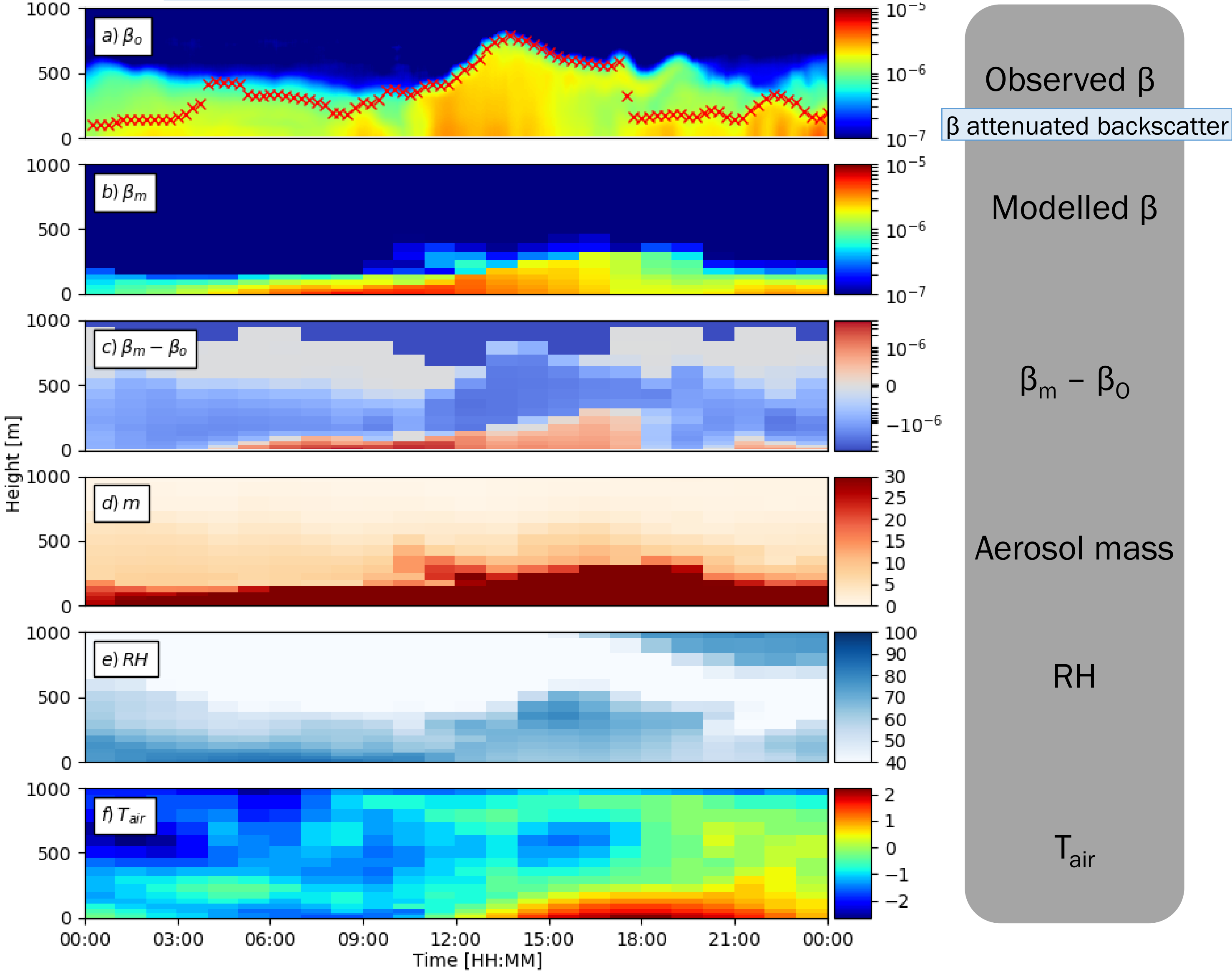


Kotthaus & Grimmond (2014a) *Urban Climate*

Operational NWP Met Office UKV with Best-1T scheme

Automatic Lidar and Ceilometer ALC

High pollution day London (19 January 2016)
Observed daily average PM_{10} > 50 μg m^{-3}

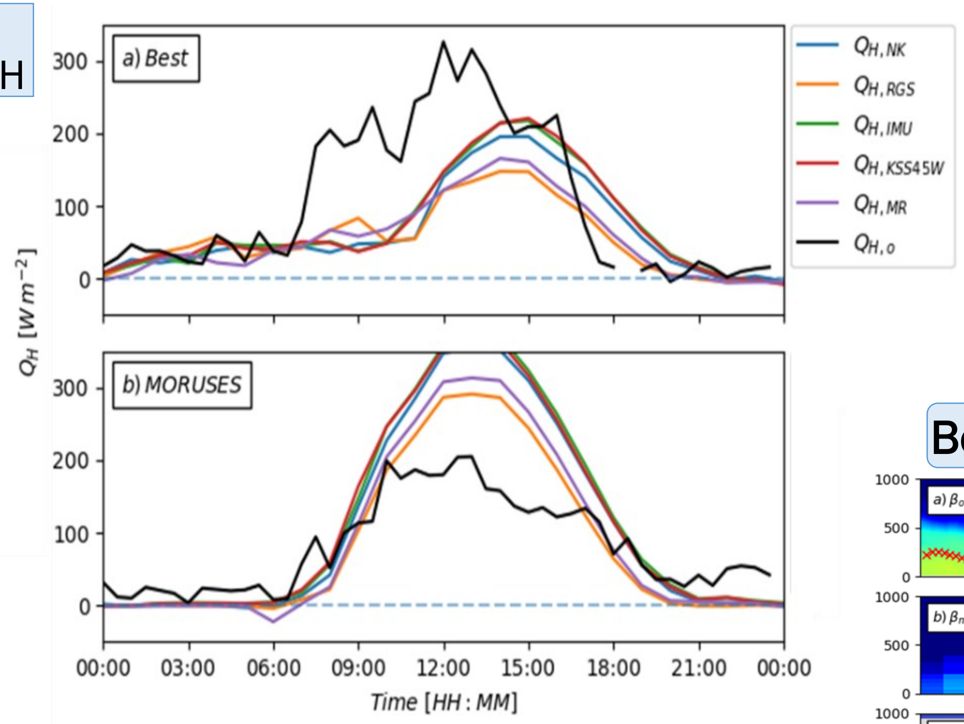


- Almost persistently high β_m near the surface
- Aerosol: insufficiently mixed in the vertical due to **lack of aerosol dispersion**
- Earlier dates – could identify emission inventory problems

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

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

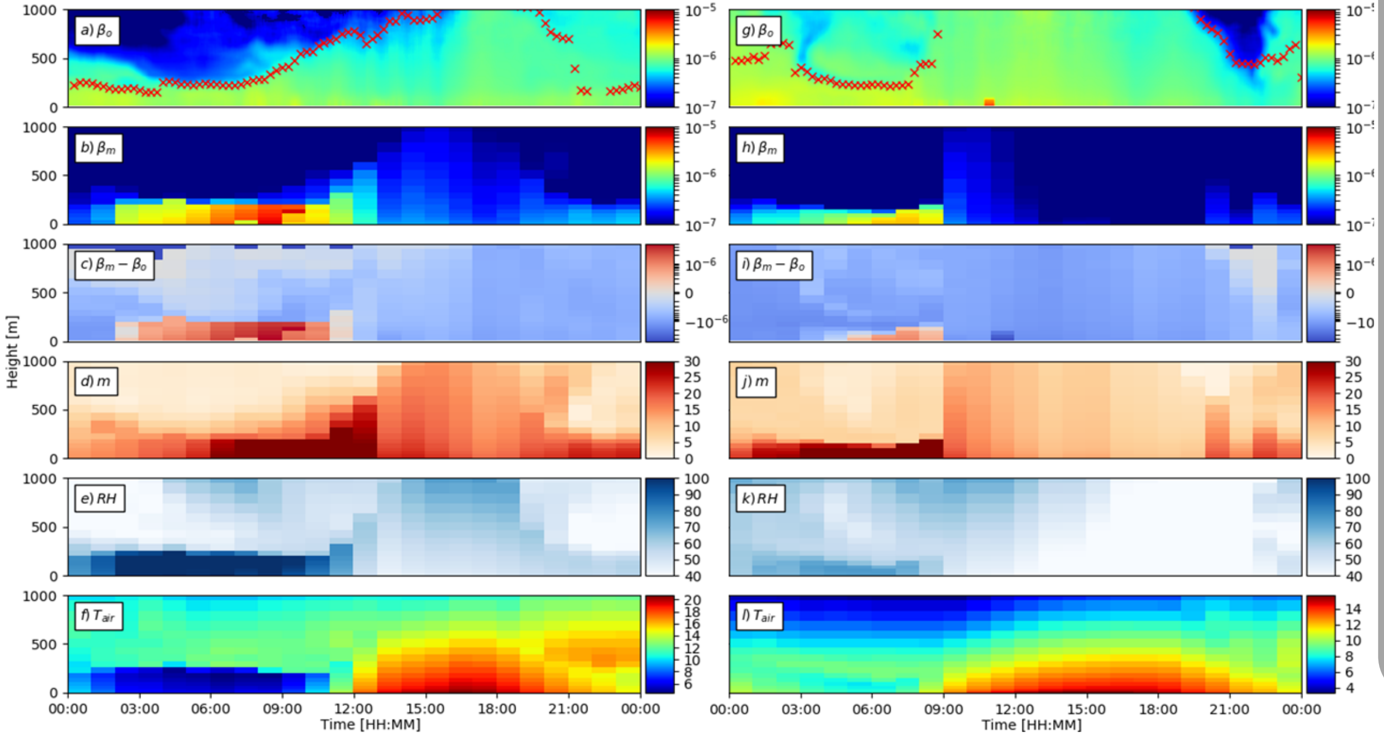
Q_H



Sensible heat flux near surface evaluation

- 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



X Observed Mixed Layer Height

Observed β

β attenuated backscatter

Modelled β

$\beta_m - \beta_o$

Aerosol mass

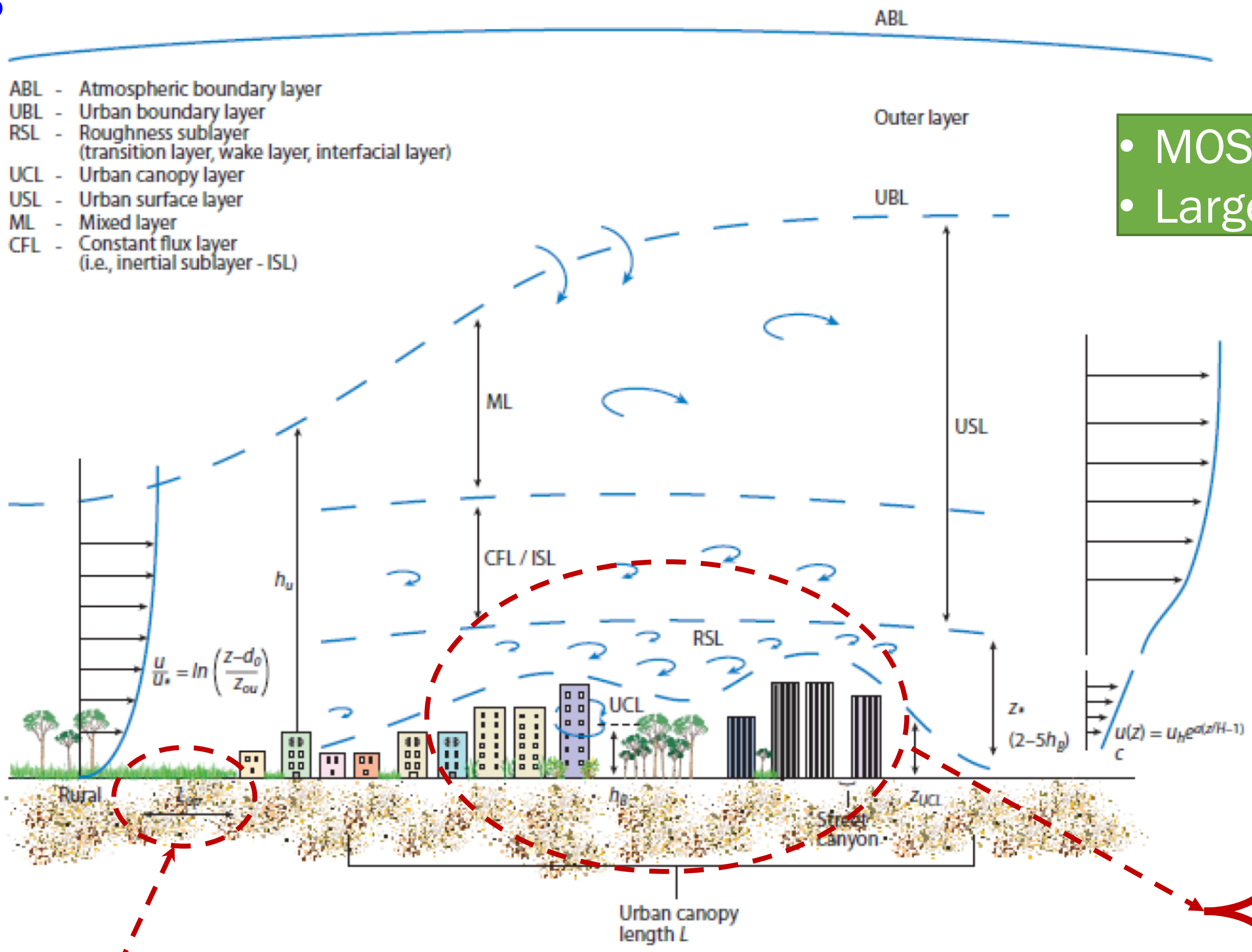
RH

T_{air}

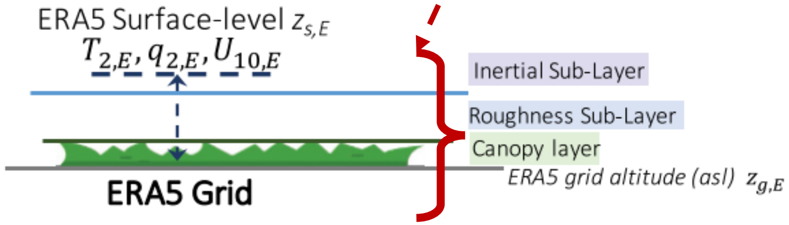
Warren et al. (2018) https://doi.org/10.1016/j.atmosenv.2018.04.045

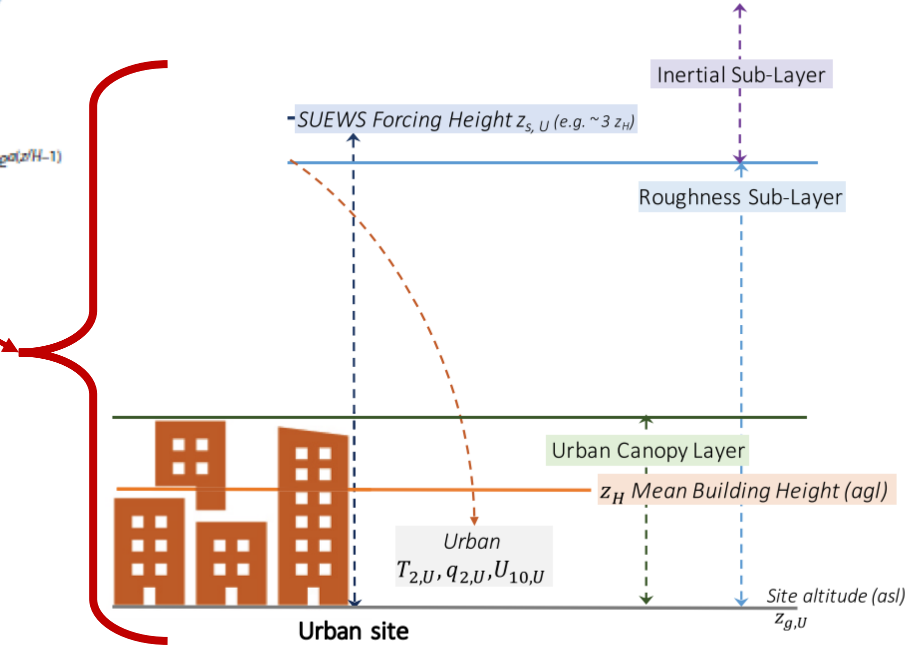
Challenges

- MOST – breaks down close to the surface
- Large roughness elements



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



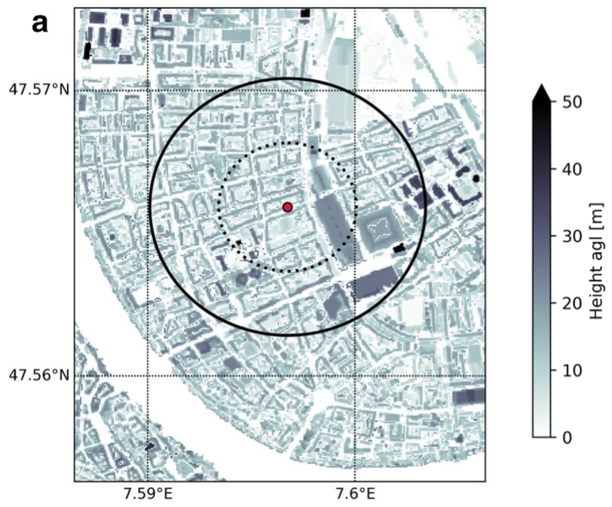


Tang et al. 2021: Building and Environment, https://doi.org/10.1016/j.buildenv.2021.108088

Wind profile close to the Urban Surface: below the Inertial Sub-Layer

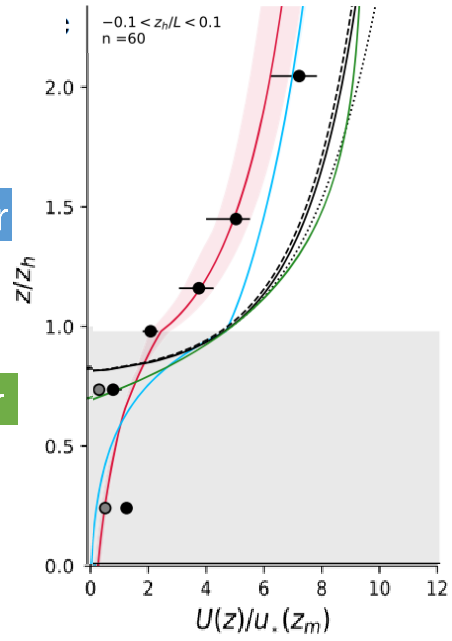
Roughness sub layer

Urban Canopy Layer



Real World Observations:
Basel-Sperrstrasse

Dense Uniform Terrain

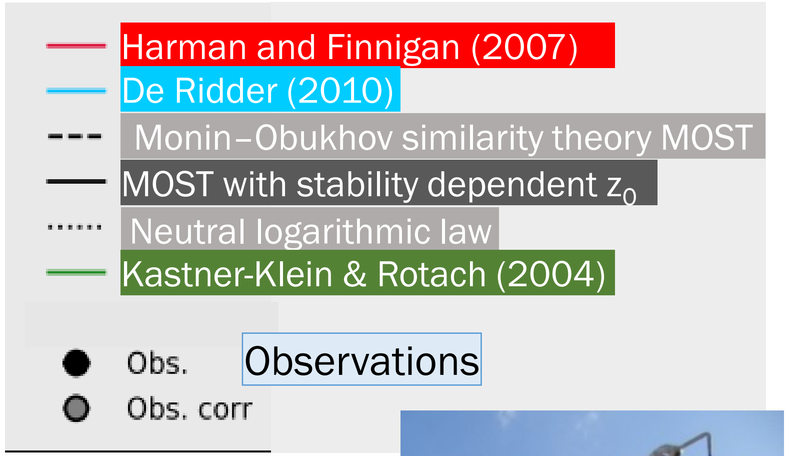


Profiles of Wind speed normalized by friction velocity

Near neutral

Wind across flat-roof buildings

Model parameterisations



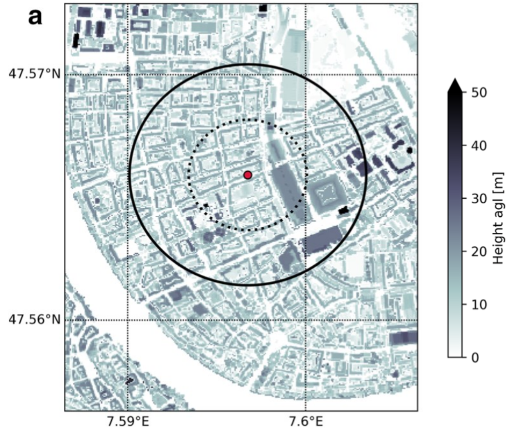
- Harman and Finnigan (2007)
- De Ridder (2010)
- Monin–Obukhov similarity theory MOST
- MOST with stability dependent z_0
- Neutral logarithmic law
- Kastner-Klein & Rotach (2004)

Observations

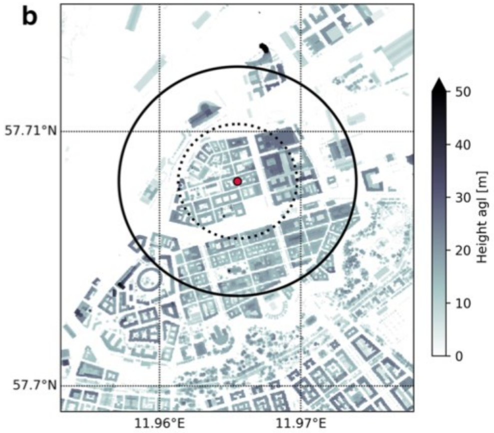
Theeuwes *et al.* (2019) *BLM* https://doi.org/10.1007/s10546-019-00472-1

Different stabilities

Wind speed profiles normalized by friction velocity



Real World Observations
Basel-Sperrstrasse
Dense Uniform Terrain
Gothenburg



very unstable | unstable | Near neutral

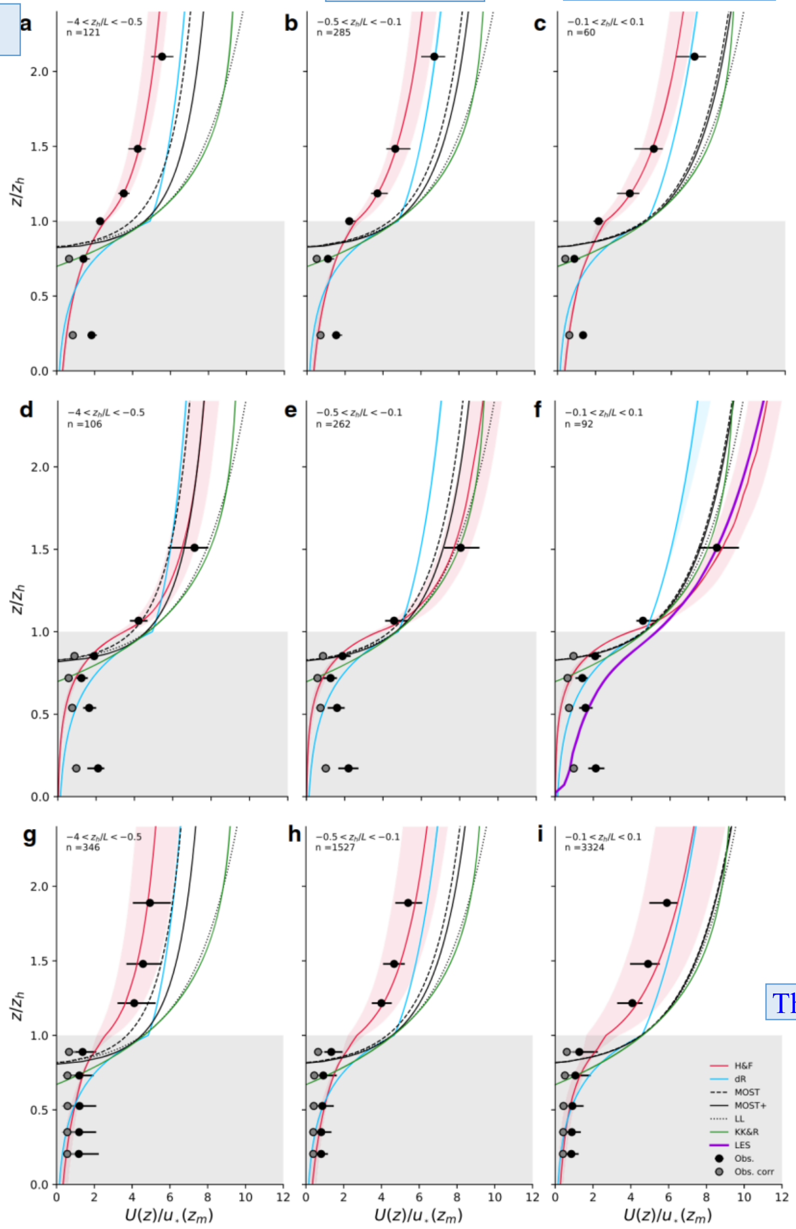
Basel-Sperrstrasse

flat-roof buildings

pitch-roof buildings

Gothenburg

perpendicular to the street canyon



Model
- Harman and Finnigan (2007)
- De Ridder (2010)
- Monin–Obukhov similarity theory
- MOST with stability dependent z_0
- Neutral logarithmic law
- Kastner-Klein & Rotach (2004)
- Giometto et al. (2016) LES

Observations
- Obs.
- Obs. corr

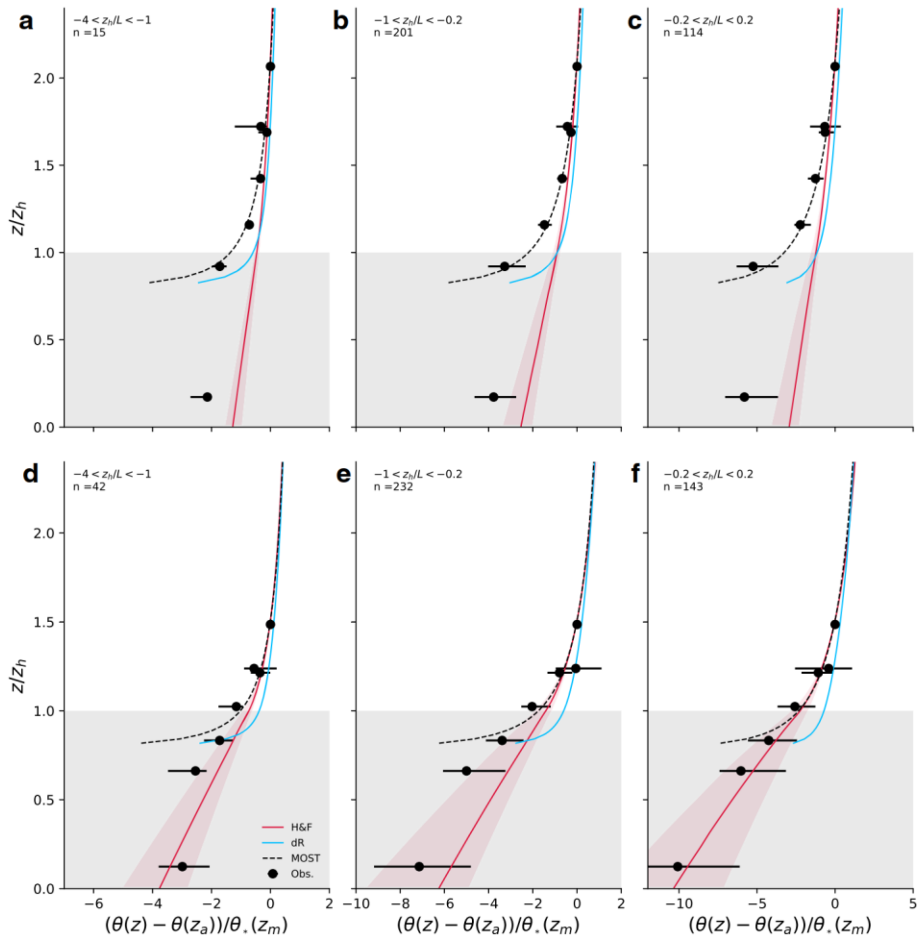
Theeuwes *et al.* (2019) *BLM* https://doi.org/10.1007/s10546-019-00472-1

Temperature Profile - Different stabilities

very unstable | unstable | Near neutral

flat-roof buildings

pitch-roof buildings



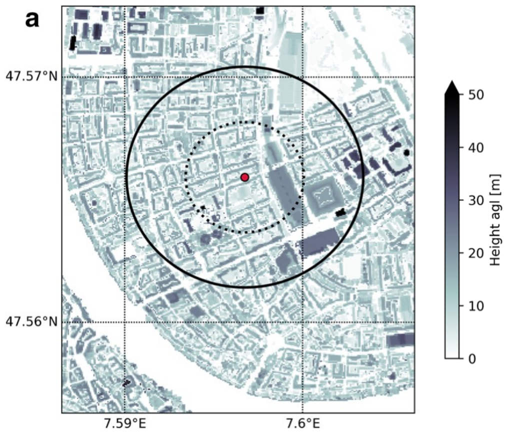
H&F — Harman and Finnigan (2007)

dR — De Ridder (2010)

MOST — Monin–Obukhov similarity theory

Obs.

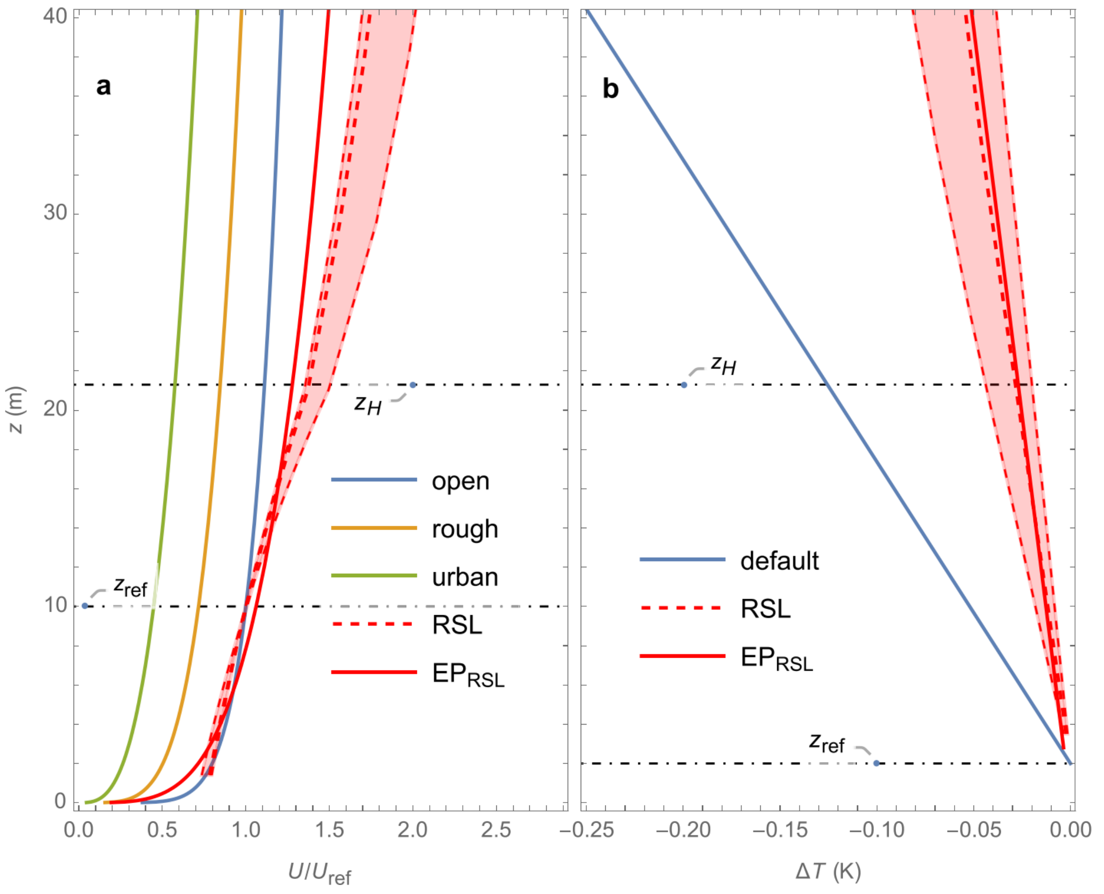
Basel-Sperrstrasse

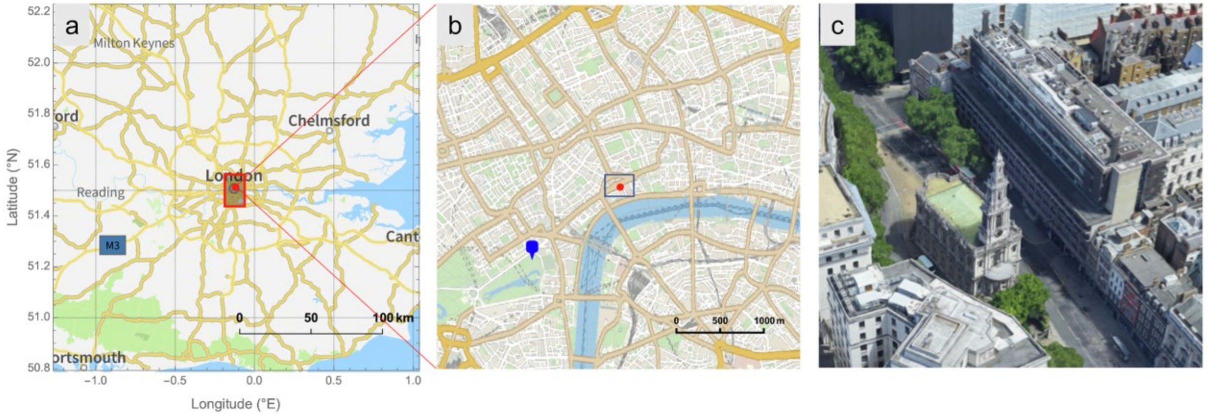


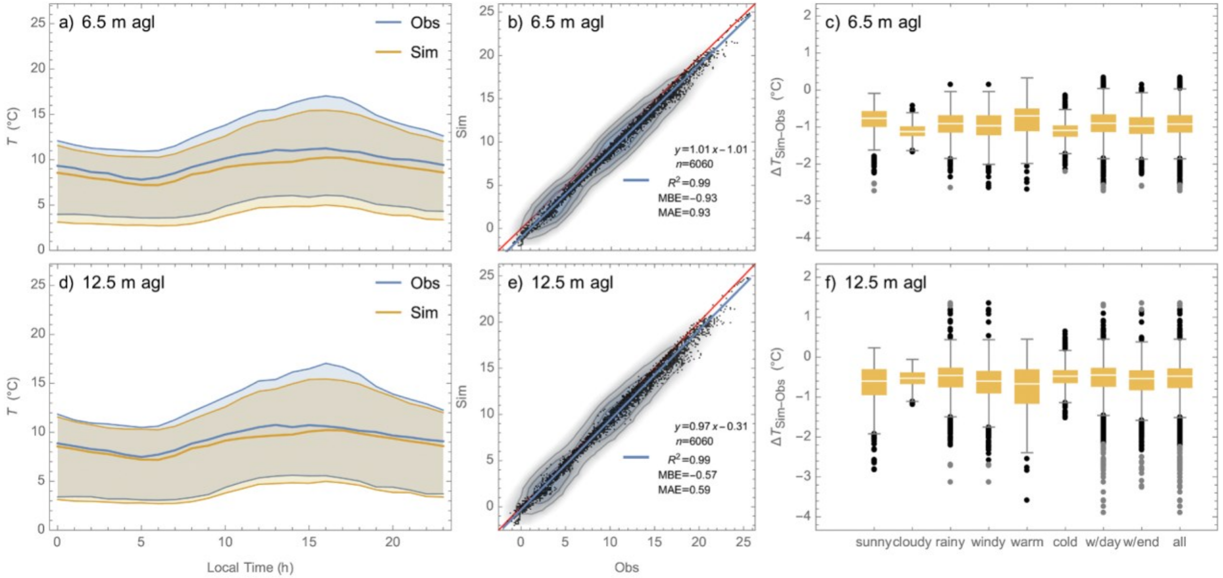
Theeuwes *et al*. (2019) *BLM* https://doi.org/10.1007/s10546-019-00472-1

SUEWS: RSL Profile Evaluation in London

- Couple Harman and Finnigan RSL model to local scale urban canopy model (SUEWS)
- Diagnose profiles down to the ground

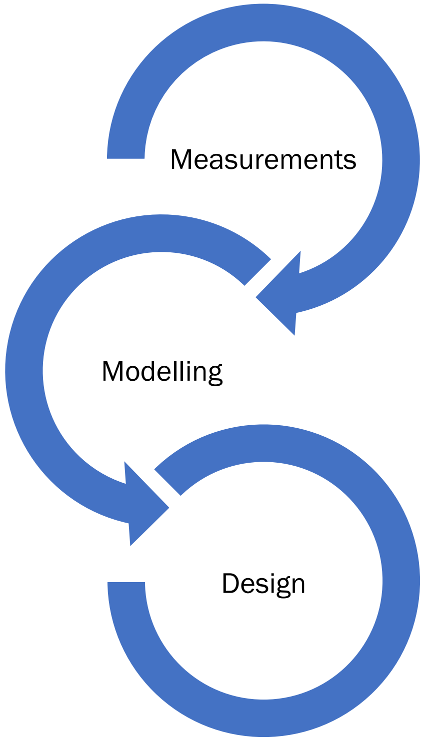






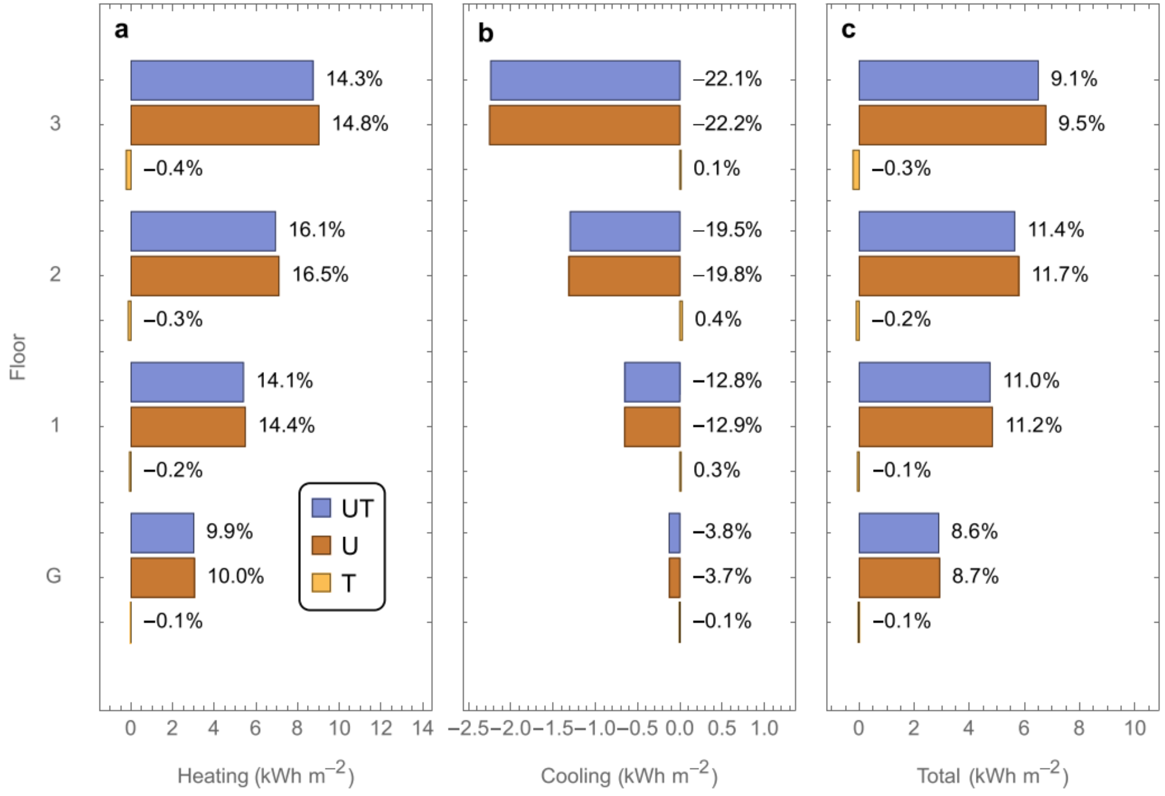
Tang et al. 2021: Building and Environment, https://doi.org/10.1016/j.buildenv.2021.108088

Implications for Building design and Energy consumption by floor

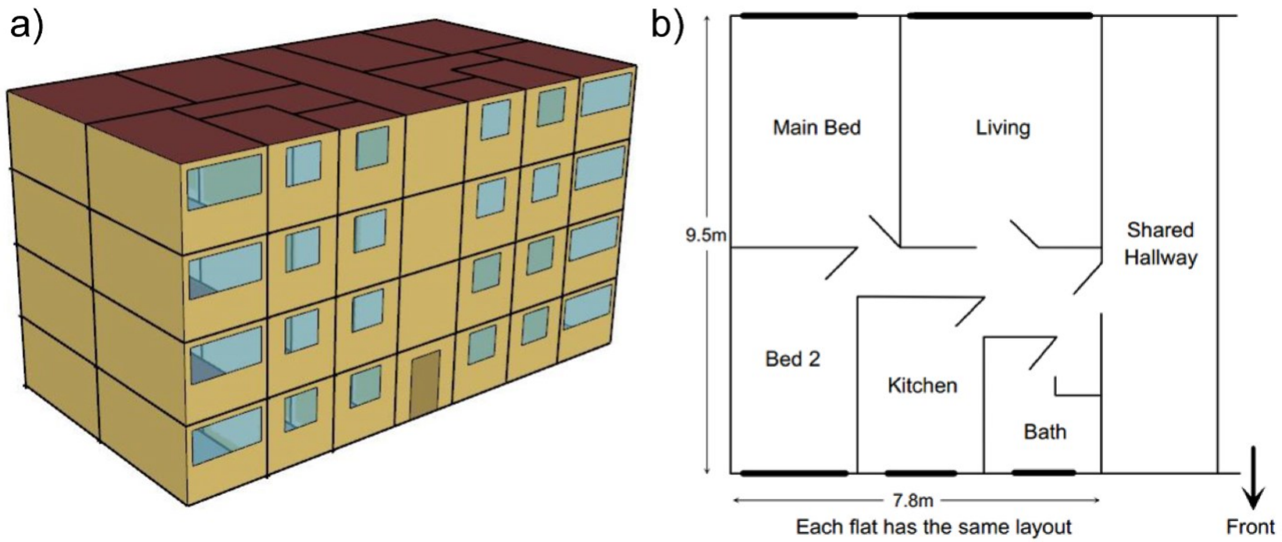


EnergyPlus simulated annual energy load

Heating Cooling Total



- Use SUEWS-RSL to force neighbourhood scale models for building energy design
- Implications: human comfort
- Energy needs, CO_2 emissions



U Wind
T Temperature
UT U & T

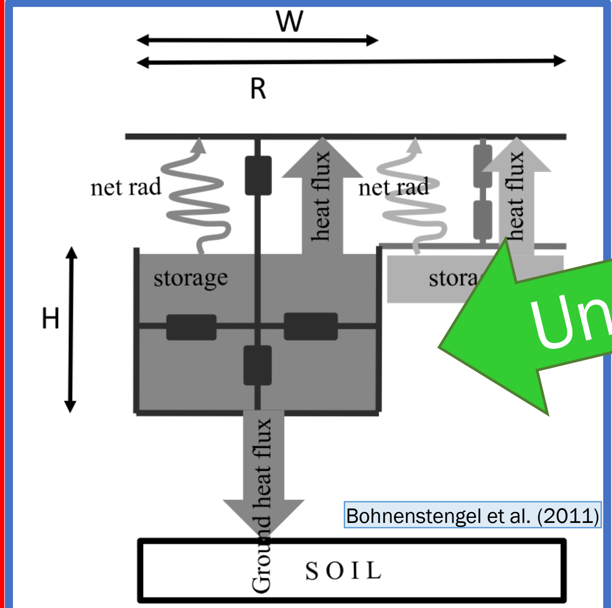
[new – default$_{open\ terrain}$]
(%): diff. normalised by open terrain values

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

Urban Characteristics

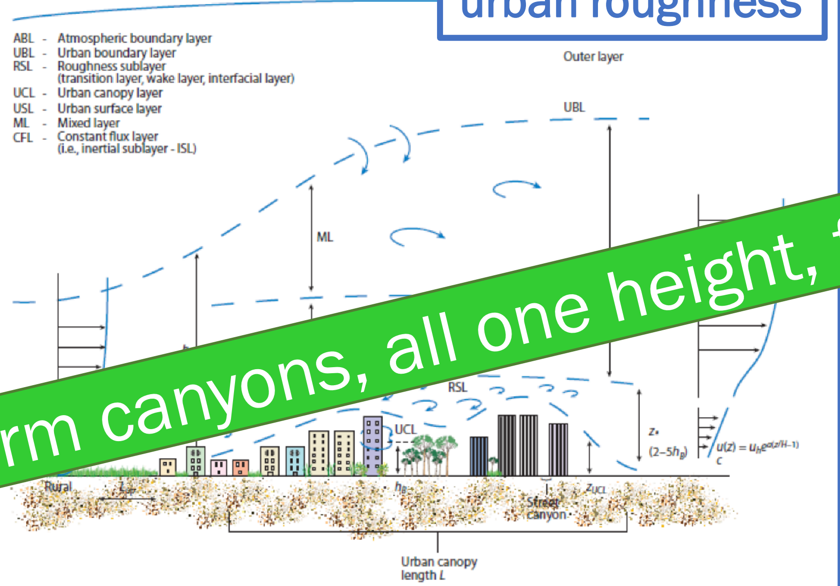
Uniform canyons, all one height, flat roofs

urban morphology

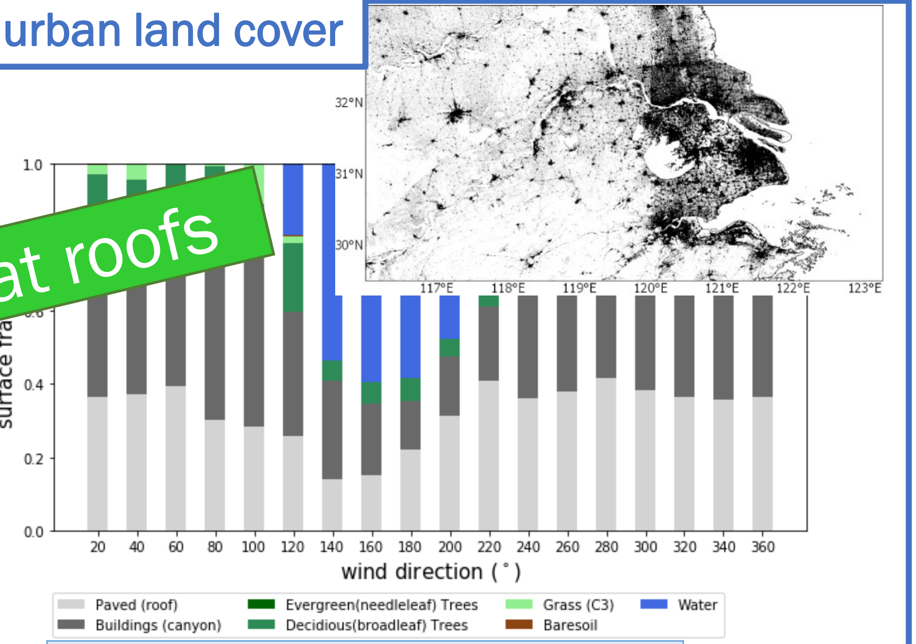


Bohnenstengel et al. (2011)

urban roughness



urban land cover



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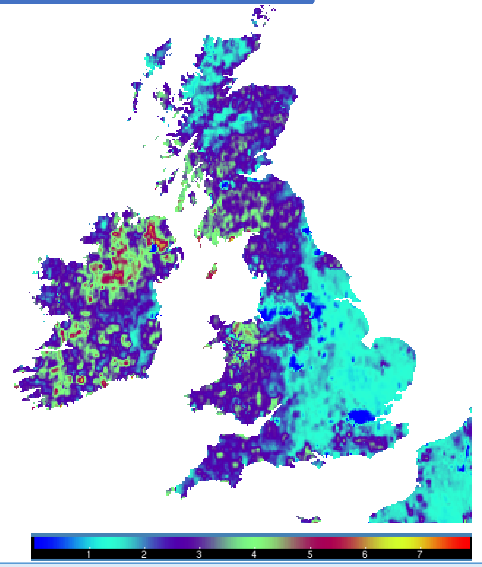
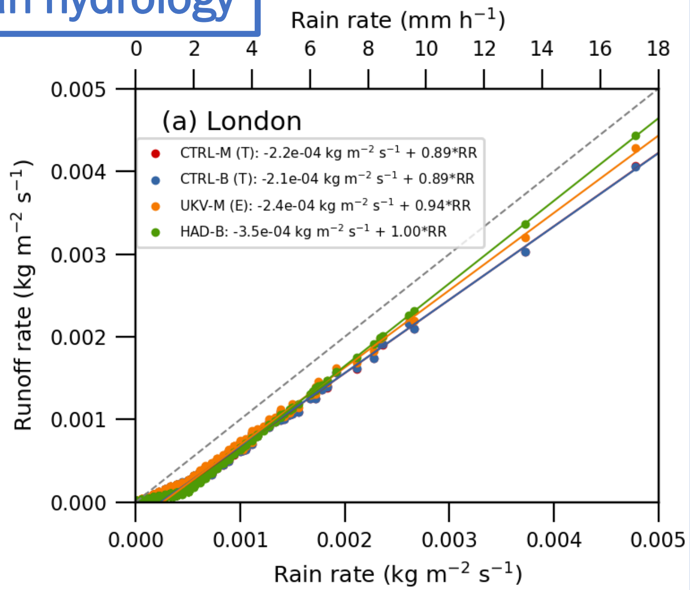
urban phenology



urban hydrology



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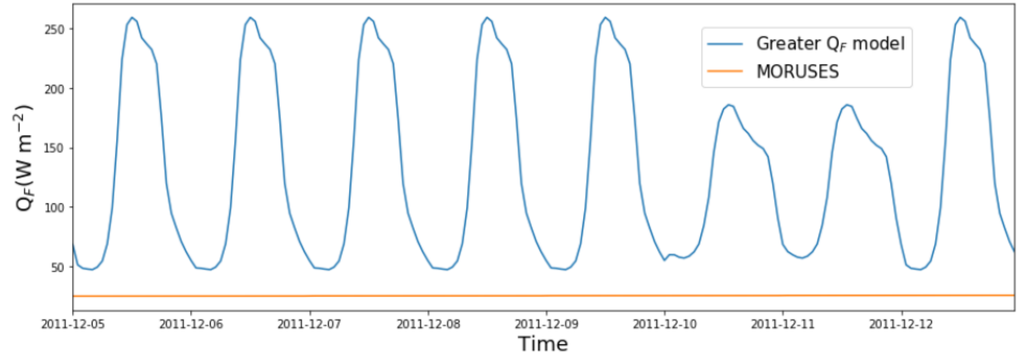
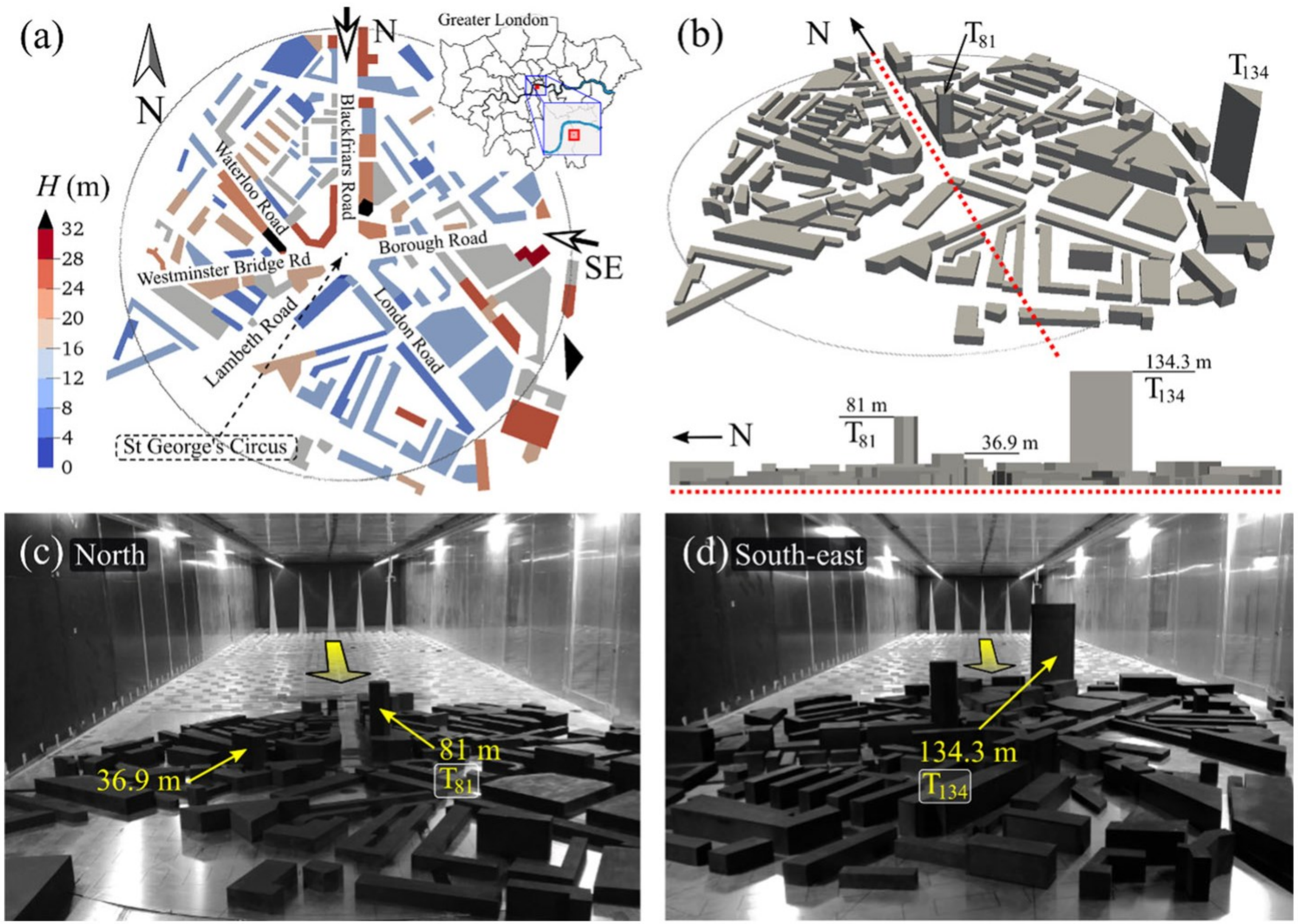
anthropogenic heat

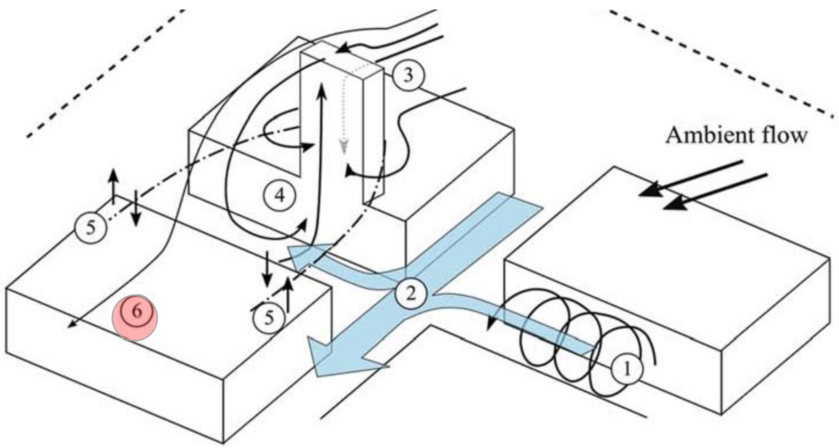
Treated as parameter- should be dynamic



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

- Many areas are more complex
- Tall buildings can have a large influence on profiles





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

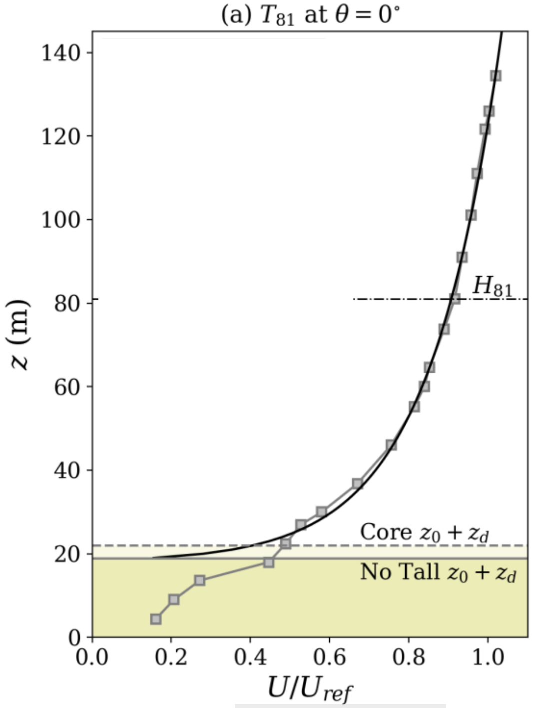
Isolated Tall Buildings (TB): London

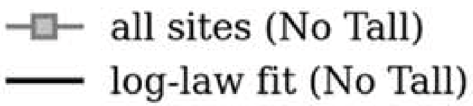
Profiles of mean longitudinal (along-wind) velocity (U/U_{ref}) ensemble averages

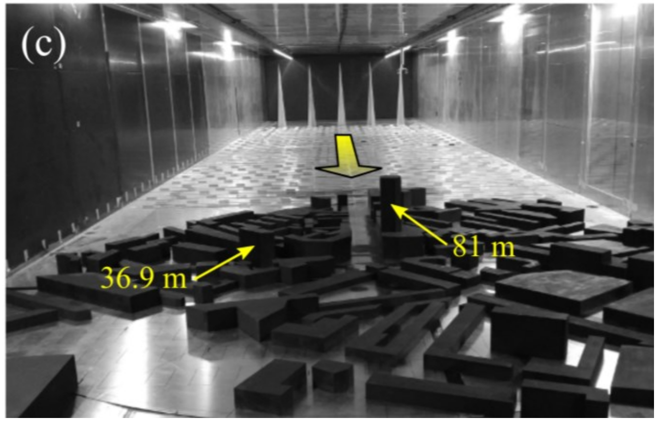
Micro

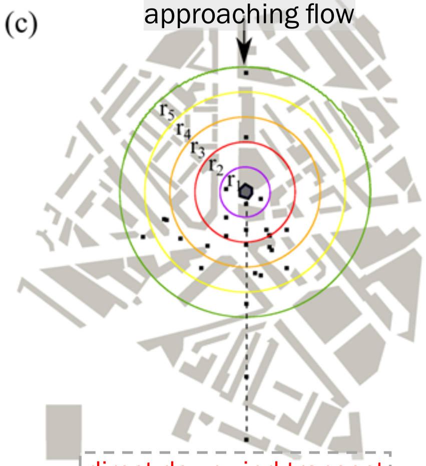
Roughness sub layer

Urban Canopy Layer



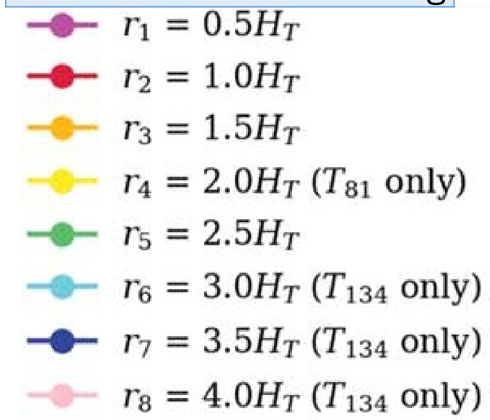






- Measurement locations
  radii (arcs, colour) - *increments of 0.5 H_{TB}*

Distances from tall building



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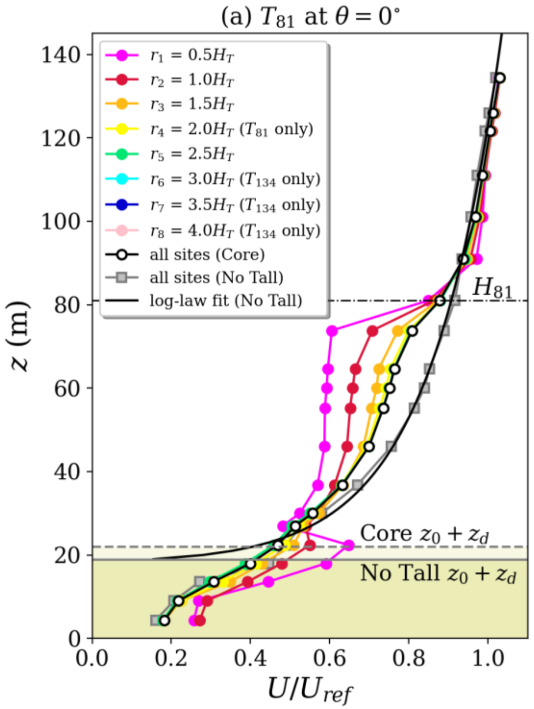
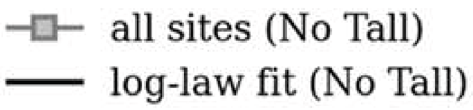
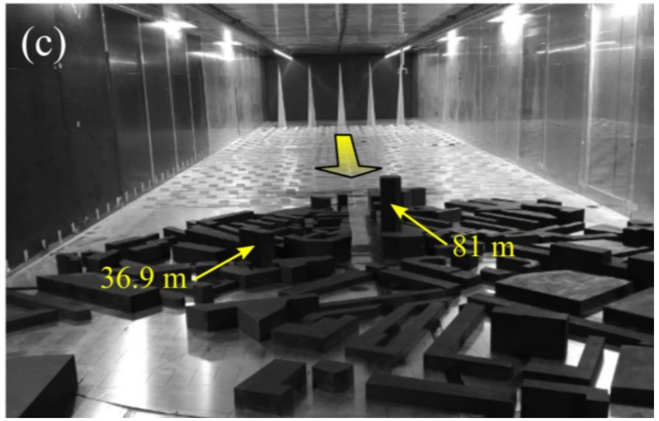
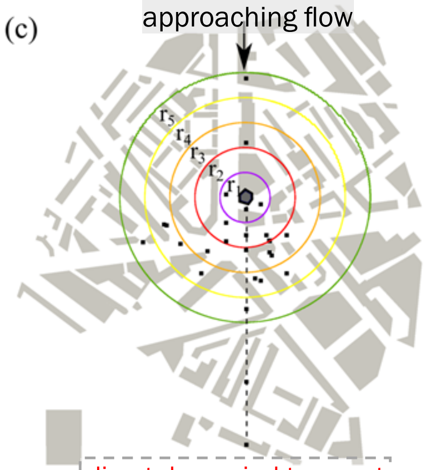




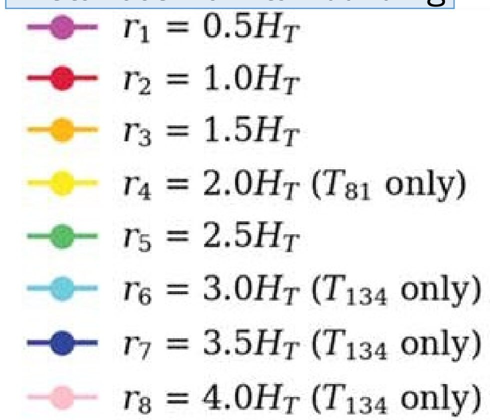




direct downwind transect in building wake

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

Distances from tall building



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

Isolated Tall Buildings (TB): London

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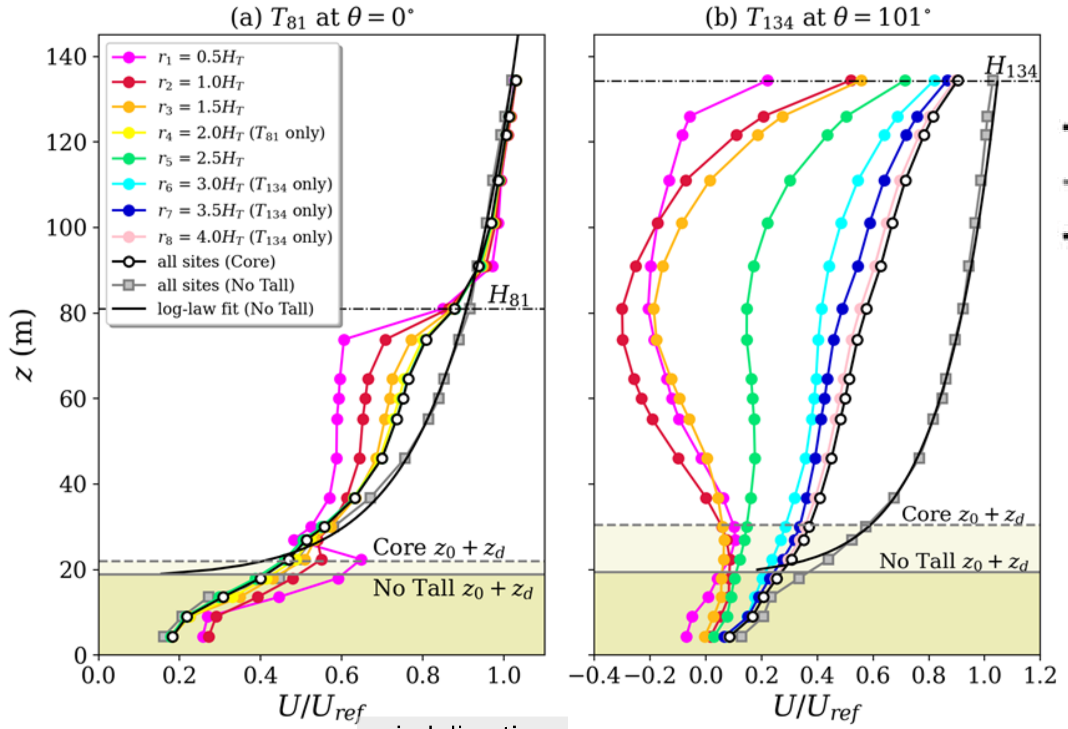
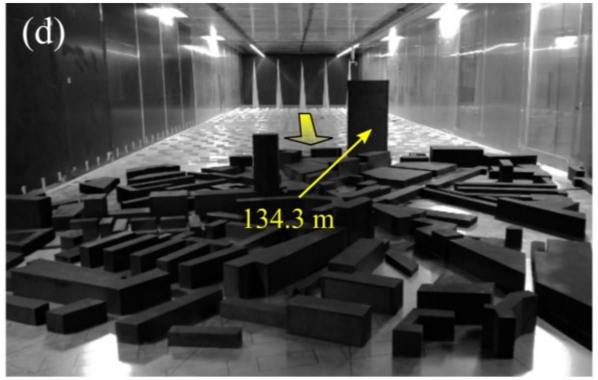
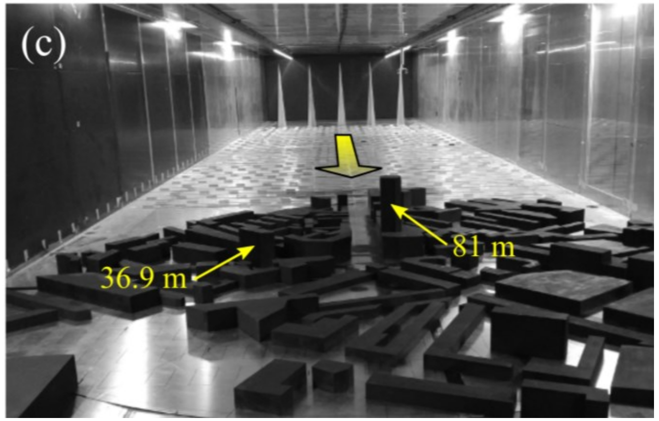


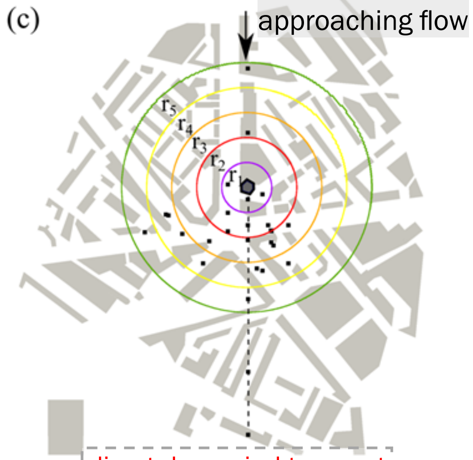
all sites (Core)

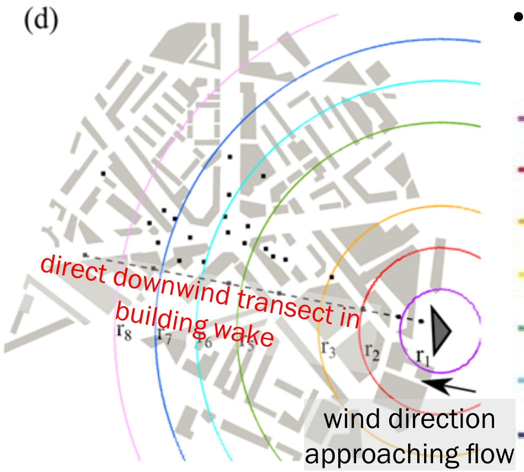
all sites (No Tall)

log-law fit (No Tall)









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

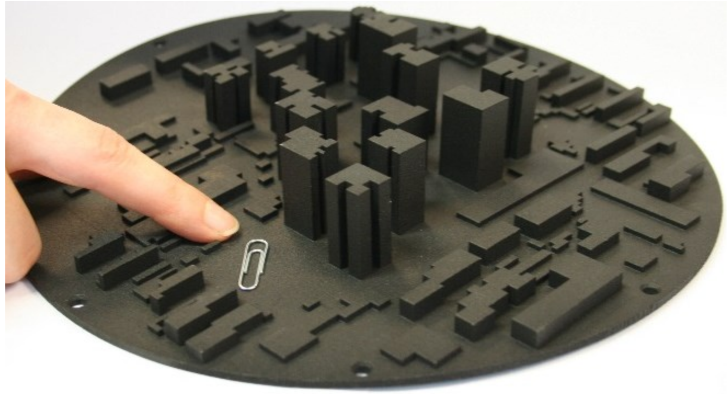
Distances from tall building

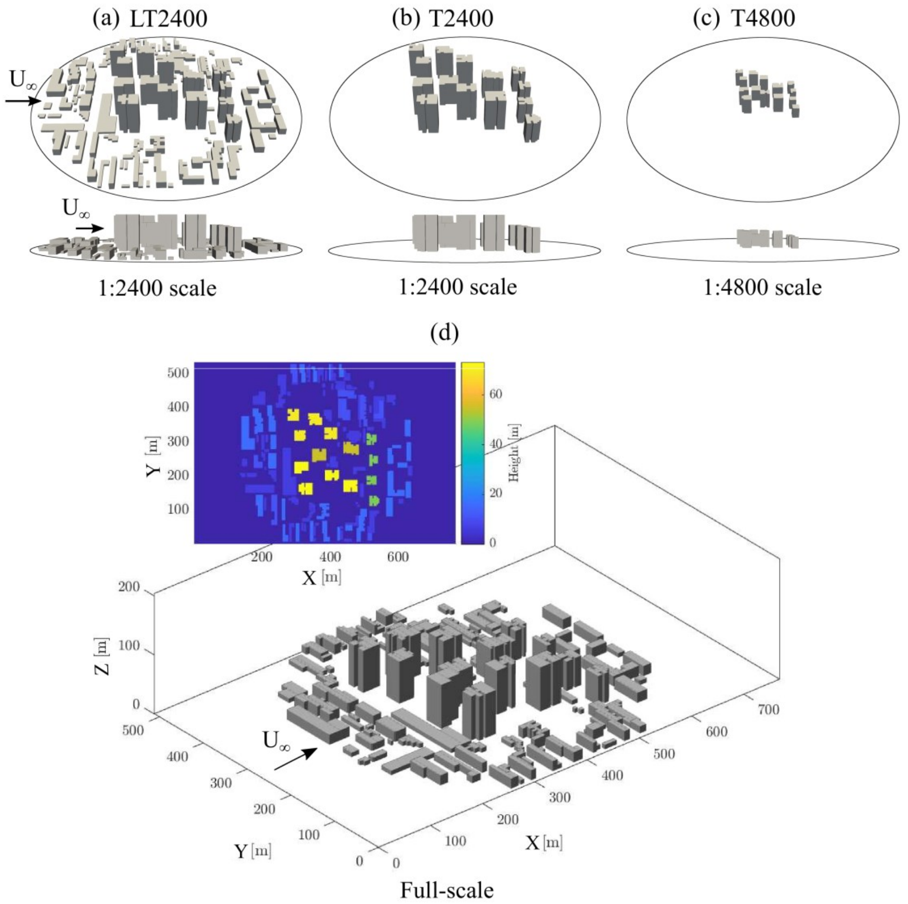
- $r_1 = 0.5H_T$
- $r_2 = 1.0H_T$
- $r_3 = 1.5H_T$
- $r_4 = 2.0H_T$ (T_{81} only)
- $r_5 = 2.5H_T$
- $r_6 = 3.0H_T$ (T_{134} only)
- $r_7 = 3.5H_T$ (T_{134} only)
- $r_8 = 4.0H_T$ (T_{134} only)

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

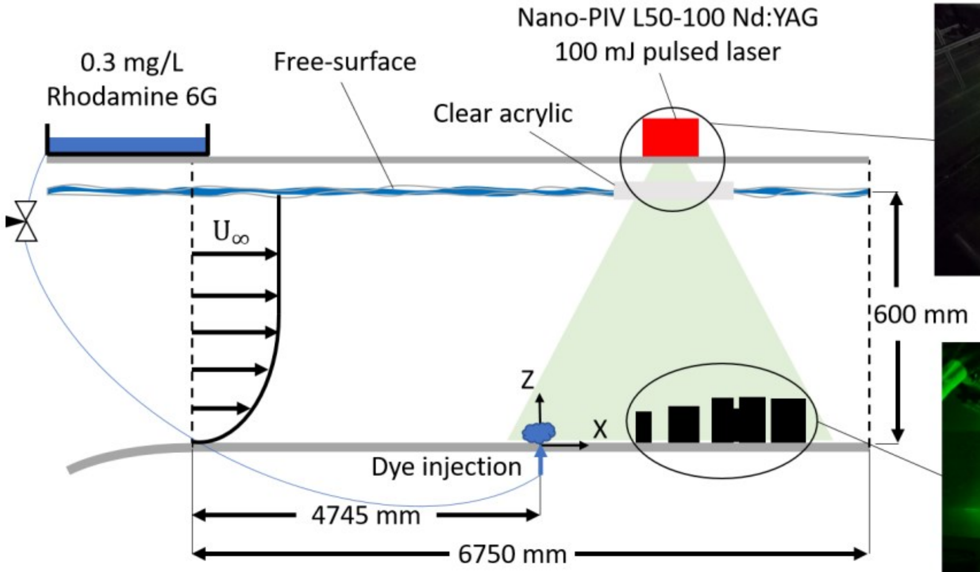
Hertwig et al. (2021) *Faraday Discussions* https://doi.org/10.1039/D0FD00098A

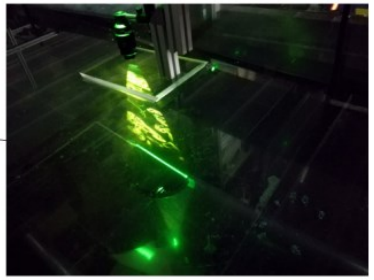
Cluster of Tall Buildings (Beijing) - Univ. of Southampton Water flume

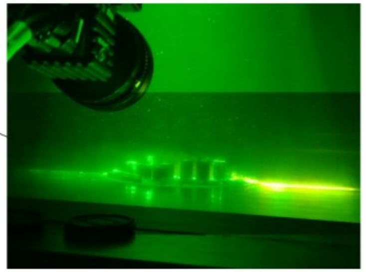




Particle Image Velocimetry (PIV) and Planar Laser Induced Fluorescence (PLIF)



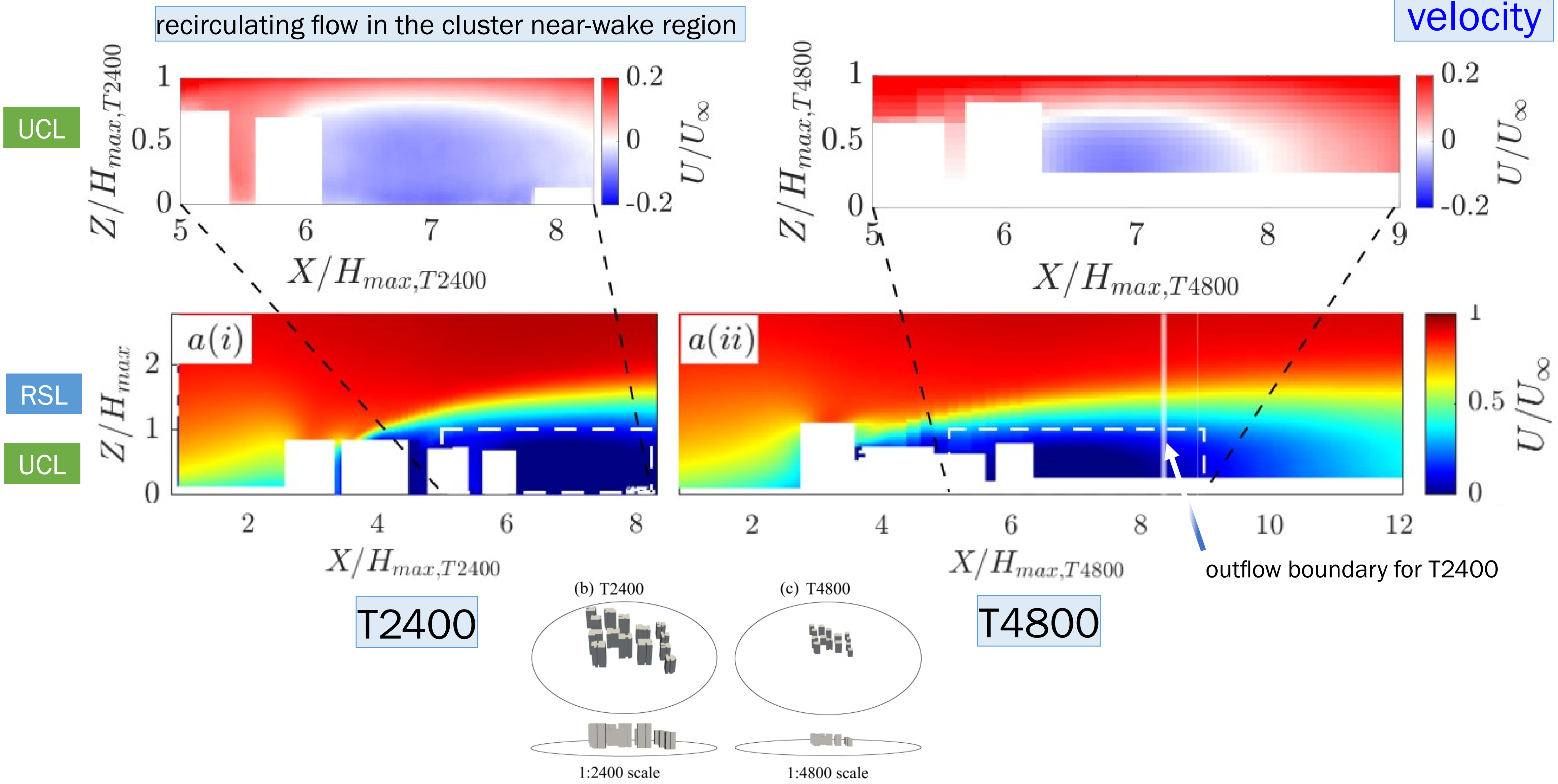




Hertwig et al. 2021 *Faraday Discussions* https://doi.org/10.1039/D0FD00098A
Lim et al. 2022: *Experiments in Fluids* 63:92 https://doi.org/10.1007/s00348-022-03439-0

Cluster of Tall Buildings (Beijing)

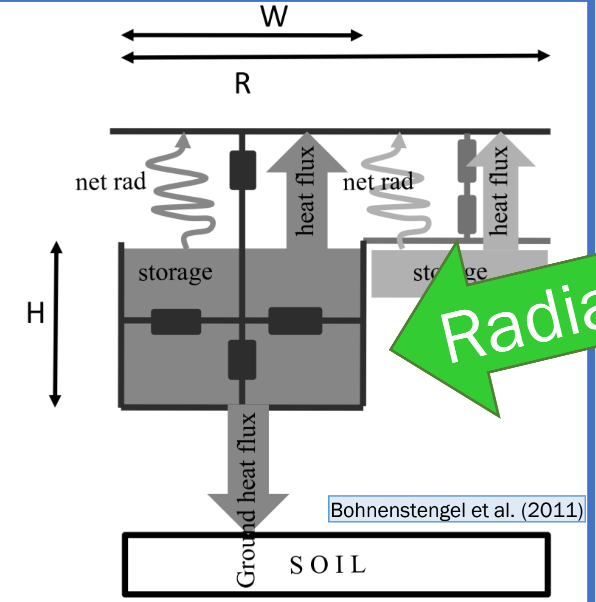
Mean velocity



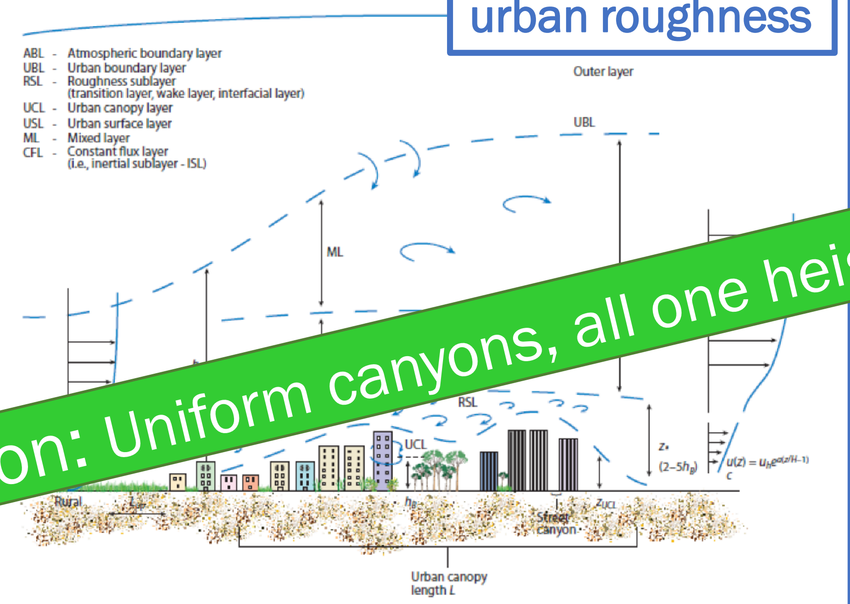
Lim et al. 2022: *Experiments in Fluids* 63:92 https://doi.org/10.1007/s00348-022-03439-0

Urban Characteristics

urban morphology

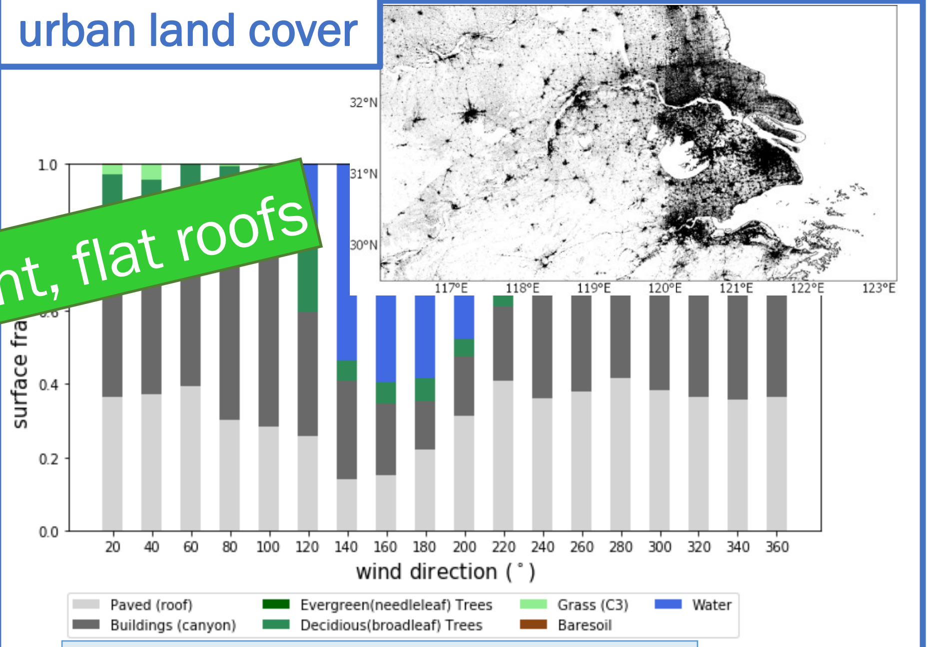


urban roughness



Radiation: Uniform canyons, all one height, flat roofs

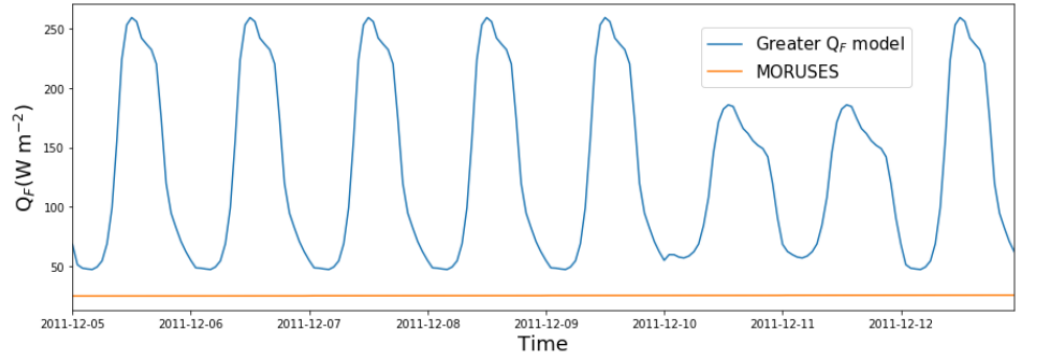
urban land cover



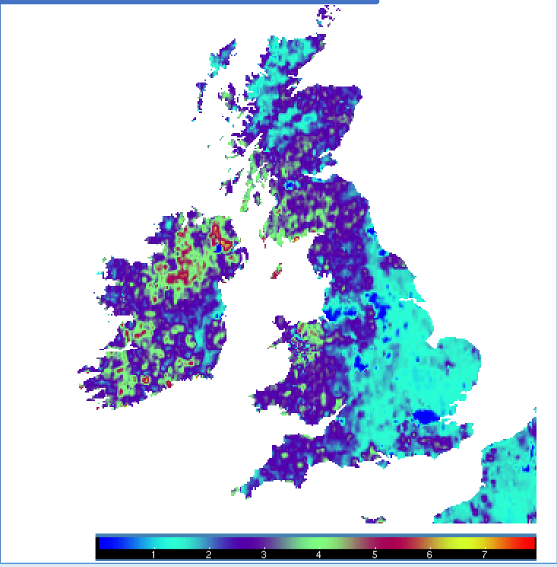
Hertwig et al. (2021) https://doi.org/10.1002/joc.7018

anthropogenic heat

Treated as parameter- should be dynamic

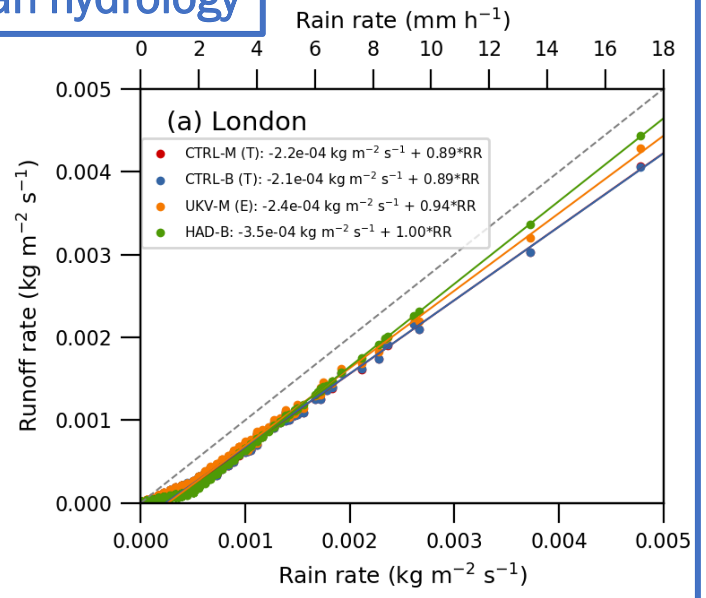


urban phenology



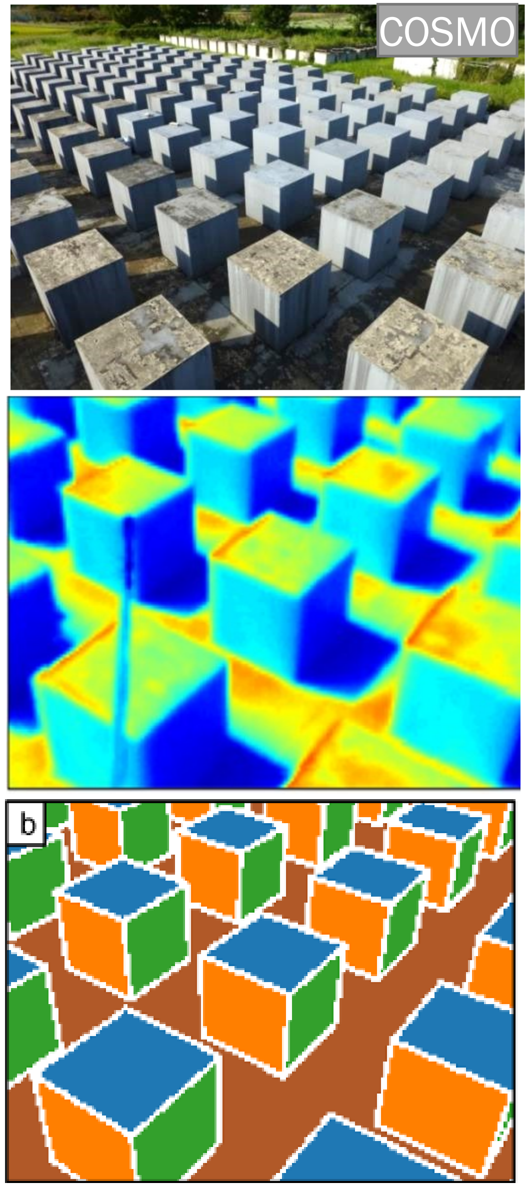
Hertwig et al. (2021) *TAAC* https://doi.org/10.1007/s00704-020-03294-1

urban hydrology

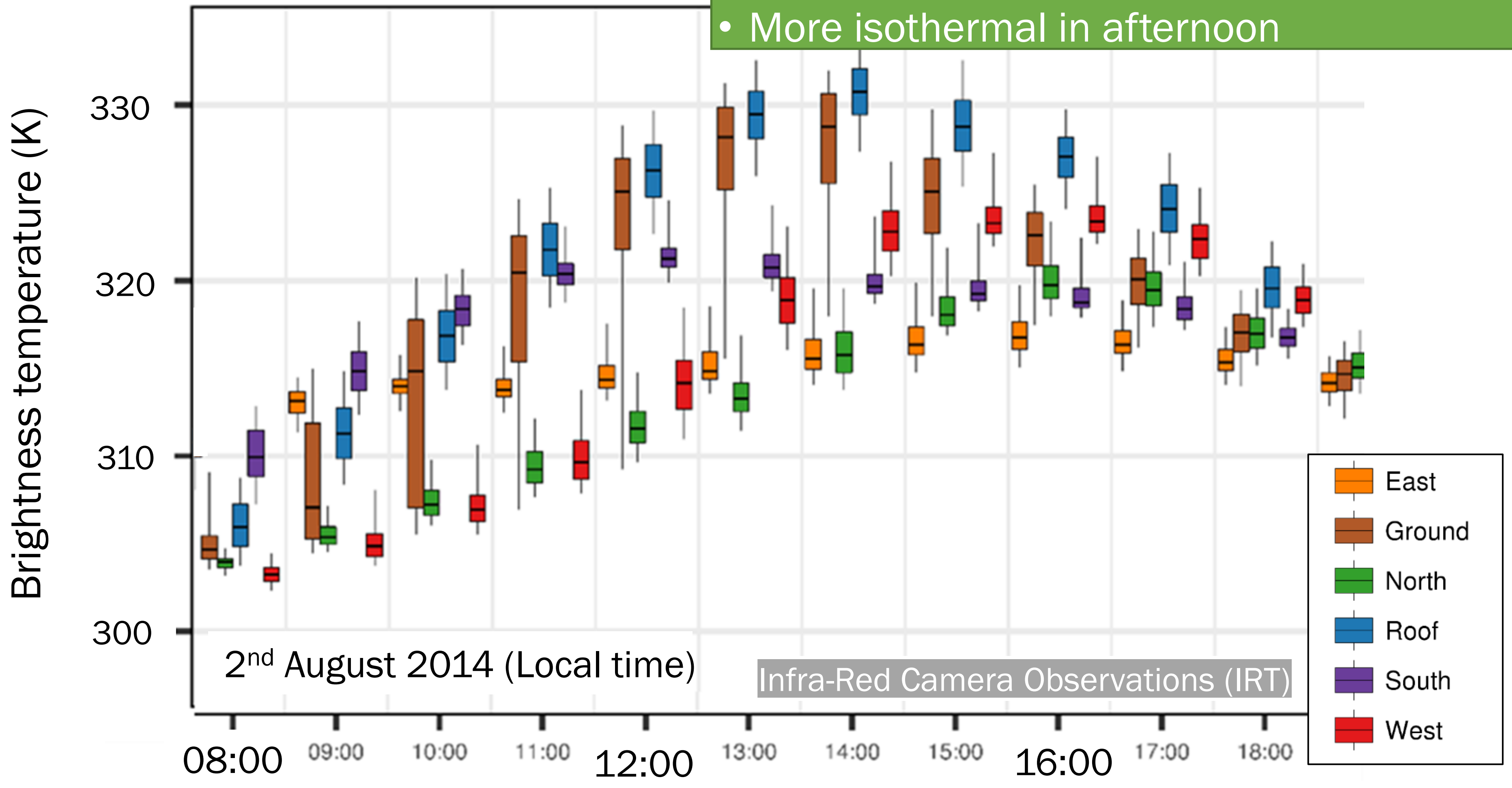


Micro-scale: Controls on variability of surface temperature

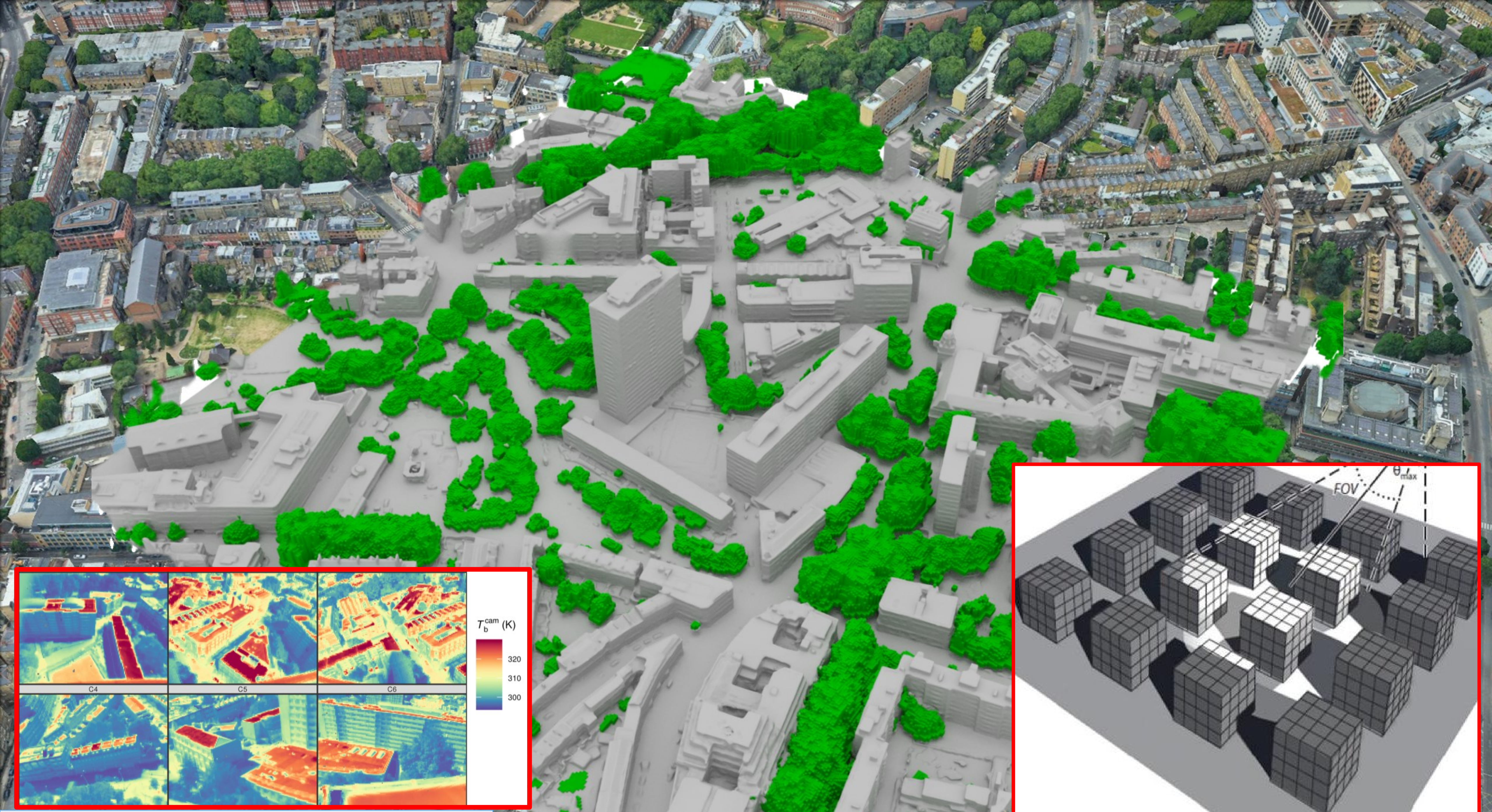
- Facet orientation



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



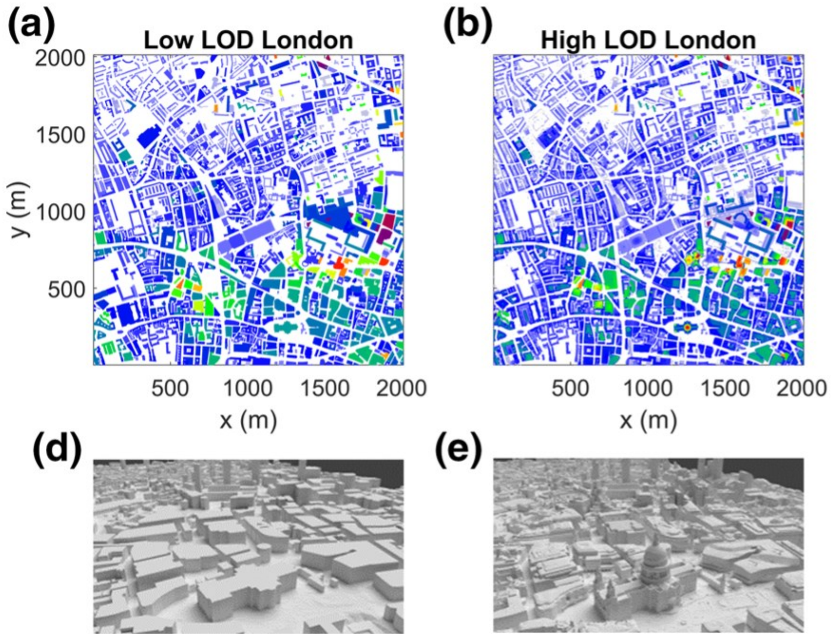
Morrison *et al*. 2018 *https://doi.org/10.1016/j.rse.2018.05.004*

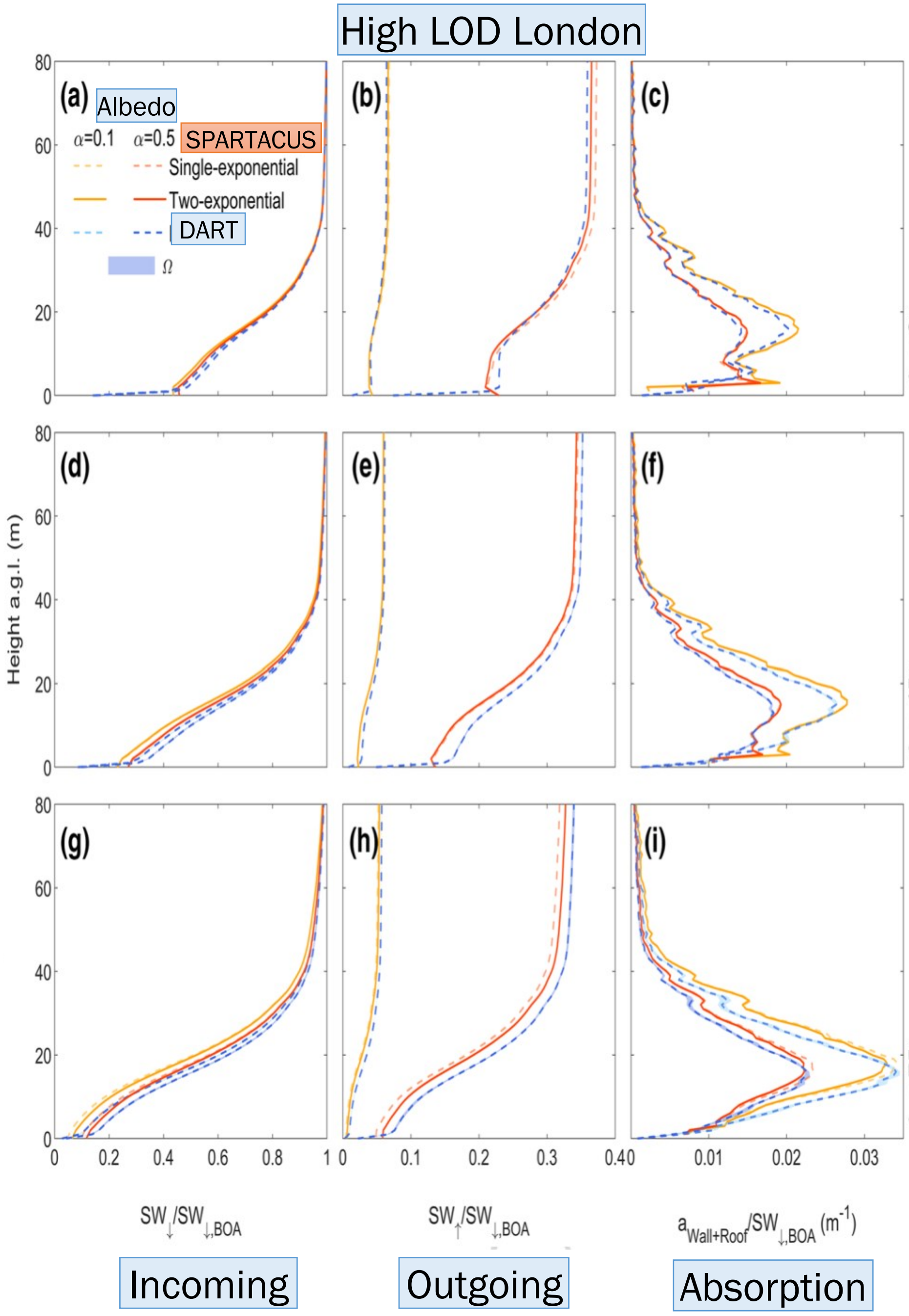


Morrison et al. (2020) https://doi.org/10.1016/j.rse.2019.111524

Shortwave Radiation

- Urban Canopy Layer Profiles
  - SPARTACUS-Surface (Hogan 2019)
  - Evaluated with: Obstacle resolving 3D modelling (DART)(Gastellu-Etchegorry et al. 2015; Landier et al. 2018)

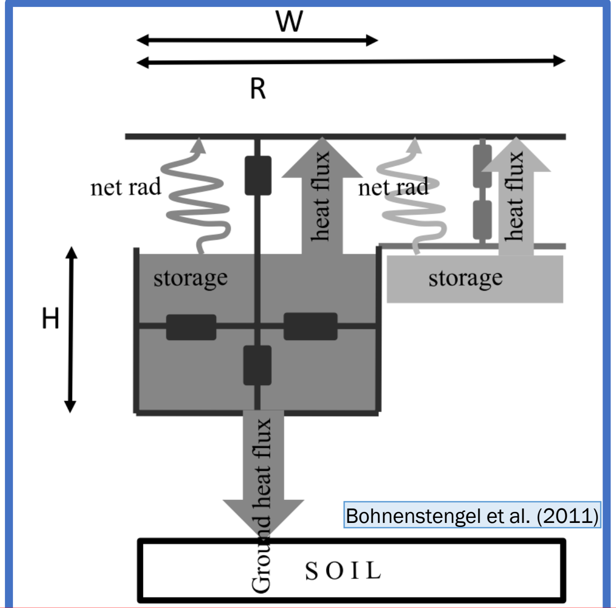




Stretton et al. 2022: *Boundary-Layer Meteorology* https://doi.org/10.1007/s10546-022-00706-9

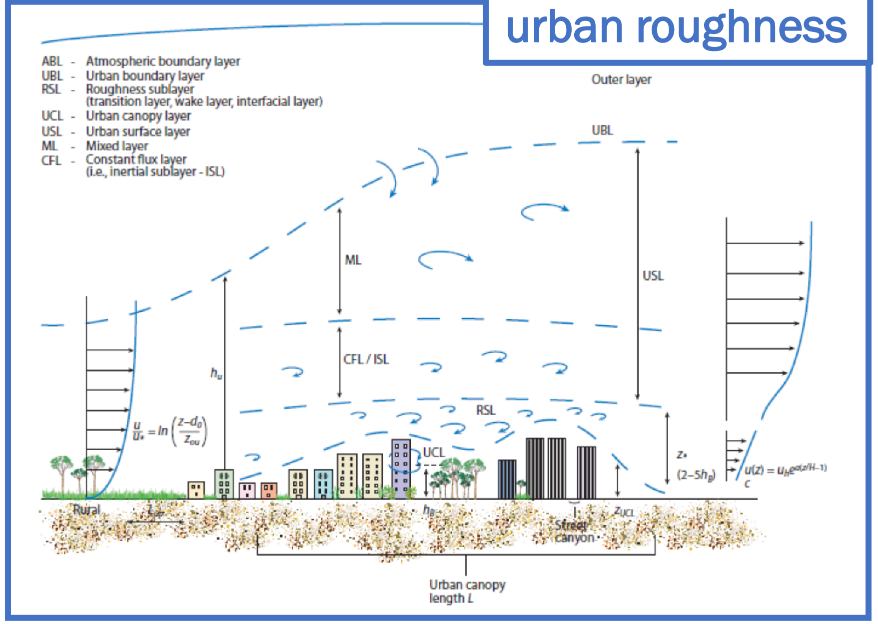
Urban Characteristics

urban morphology

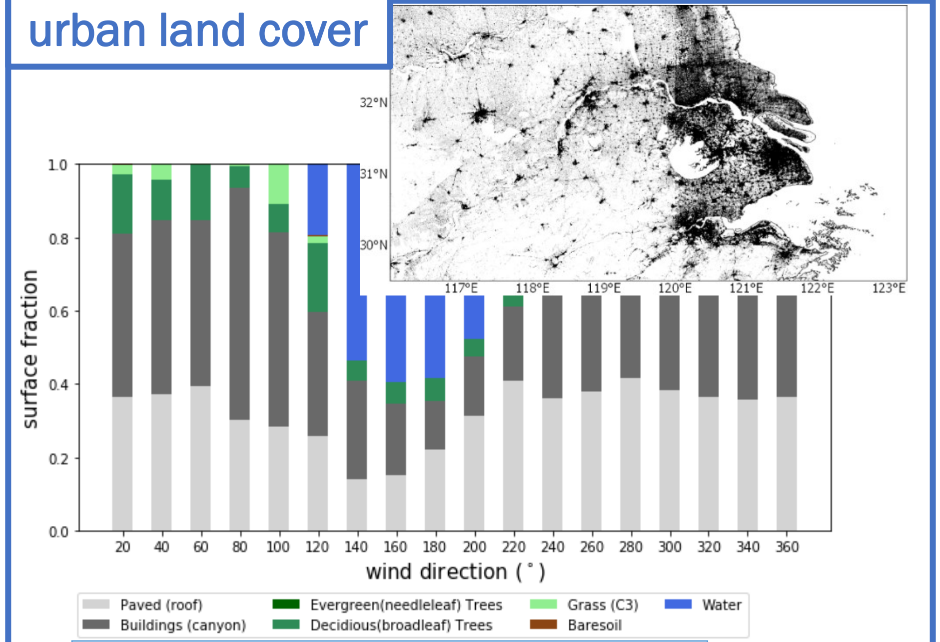


Bohnenstengel et al. (2011)

urban roughness



urban land cover



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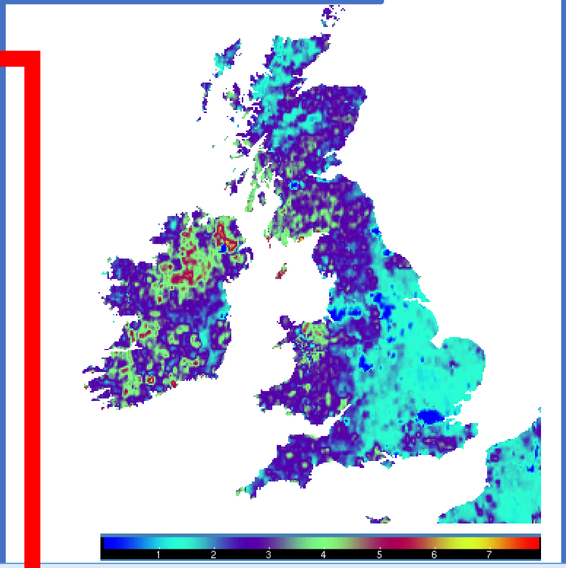
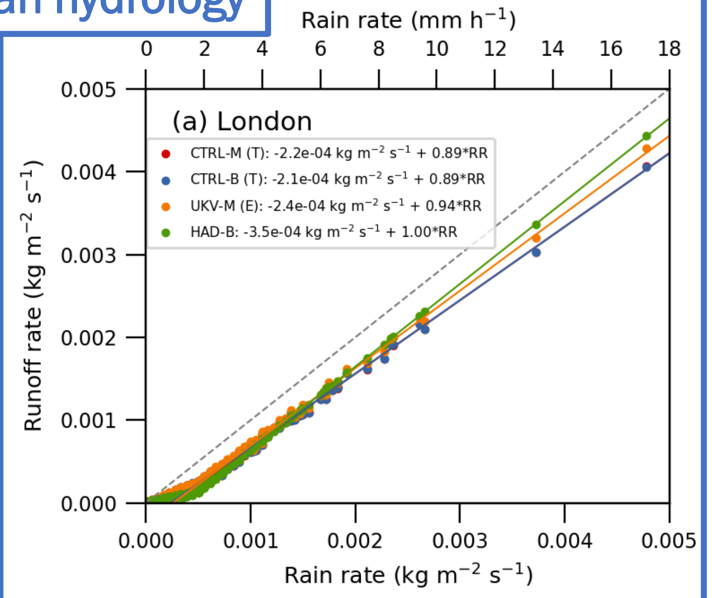
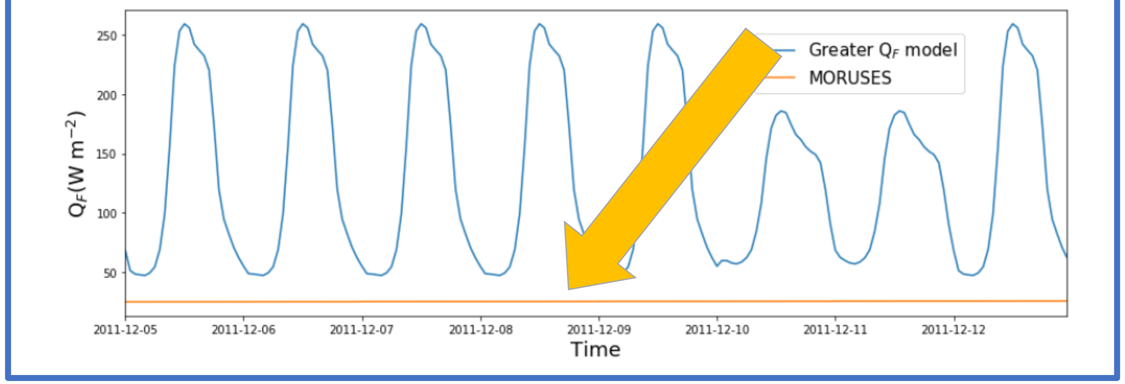


urban hydrology



Anthropogenic heat

Treated as parameter- should be dynamic

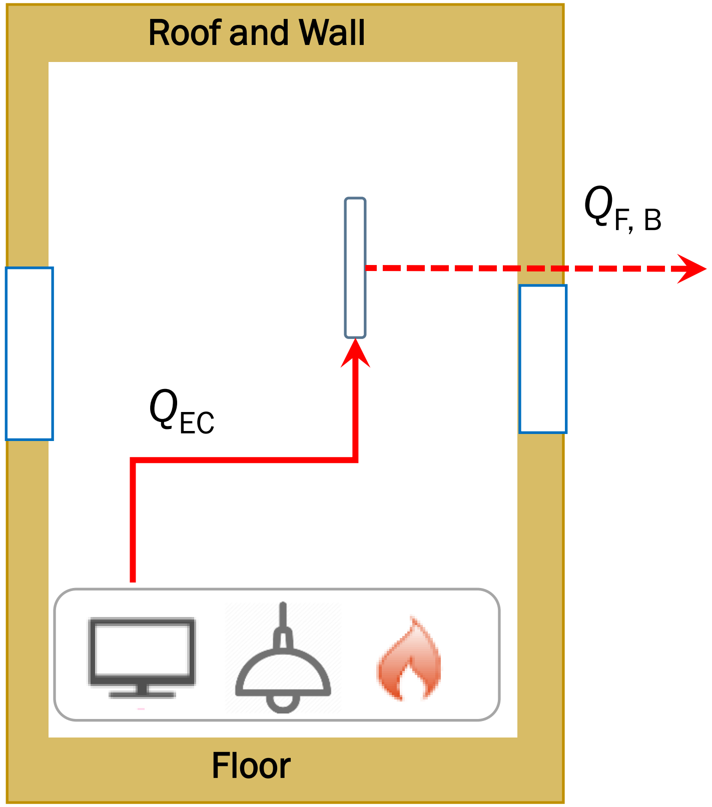


Hertwig et al. (2021) *TAAC* https://doi.org/10.1007/s00704-020-03294-1

Anthropogenic heat flux from buildings $Q_{F,B}$

- Inventory methods to estimate $Q_{F,\,B}$ ⇨ Building energy consumption data

⇩



Assumptions:

$$Q_{F,\,B} = Q_{EC}$$

Consumed energy is emitted outdoors immediately

Liu et al. 2022: *Atmos. Chem. Phys.*, 22, 4721–4735, https://doi.org/10.5194/acp-22-4721-2022

New expression for Anthropogenic heat flux from buildings $Q_{F,B}$

Occupied building (*o*)

−

Unoccupied building (*uo*)

=

Energy balance difference (*o-uo*)

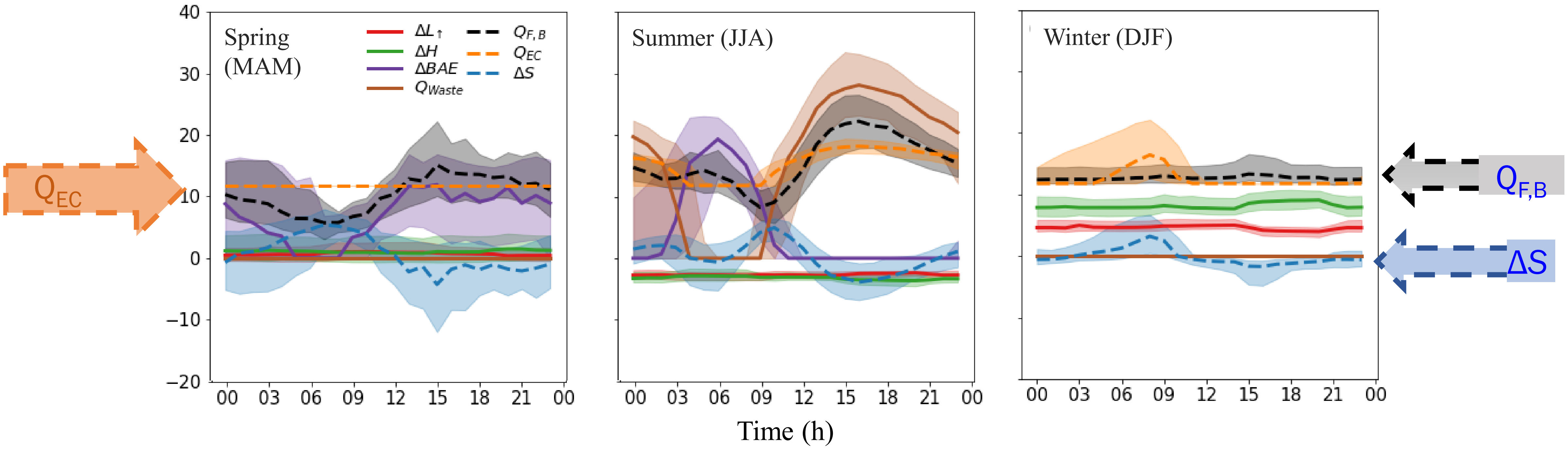
$$Q_{F,B} = Q_{EC} - \Delta S_{o - uo}$$

K^*	New shortwave radiation	o	Occupied building	$Q_{F,B}$	Anthropogenic heat flux from building
L	Longwave radiation	uo	Unoccupied building	Q_{EC}	Building energy consumption (including human metabolism)
Q_H	Turbulent sensible heat	↑	Outgoing	ΔS	Change in heat storage flux induced by human activities
ΔQ_S	Storage heat flux	↓	Incoming	o-uo	Difference between occupied and unoccupied
Q_{BAE}	Heat exchange by air exchange		Internal heat from lighting, appliance and metabolism		
Q_{Waste}	Waste heat from HVAC		Space heating and cooling		

Liu et al. 2022: *Atmos. Chem. Phys.*, 22, 4721–4735, https://doi.org/10.5194/acp-22-4721-2022

Simulation Results

- Difference between $Q_{F,B}$ and Q_{EC}: attributable to change in storage heat flux (ΔS)
- Dynamic natural ventilation: key factor in diurnal shape of $Q_{F,B}$ and ΔS in spring
- Two main driving forces: natural ventilation and space cooling determine summer $Q_{F,B}$ diurnal pattern
- No natural ventilation and space cooling: less $Q_{F,B}$ diurnal variation in Winter



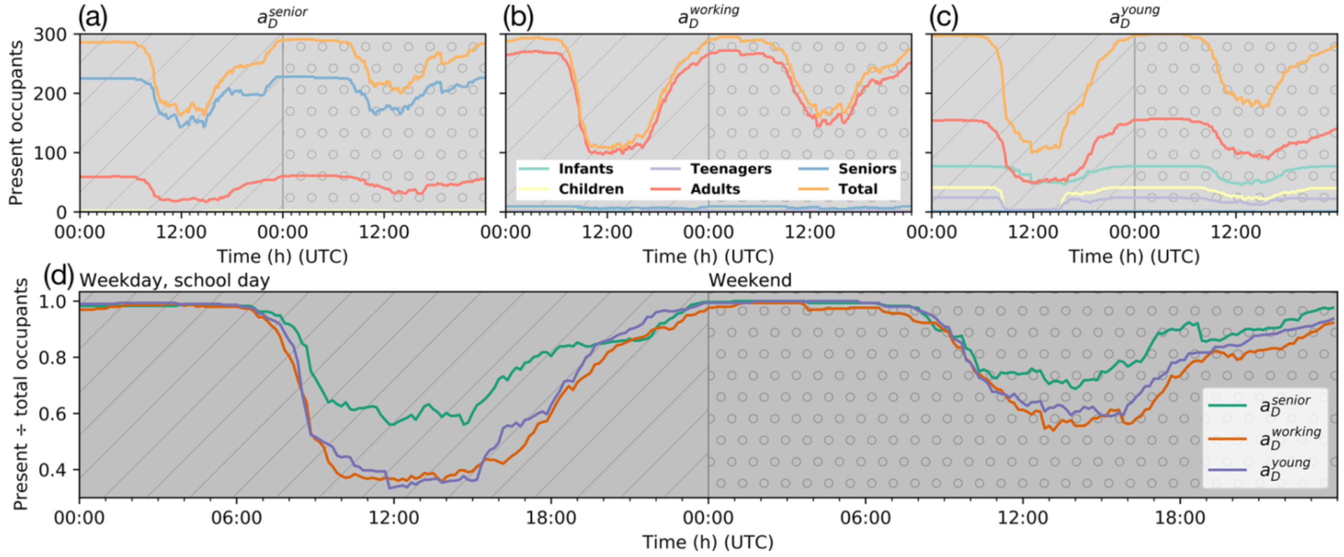
Liu et al. 2022: *Atmos. Chem. Phys.*, 22, 4721–4735, https://doi.org/10.5194/acp-22-4721-2022

Behaviour Impacts at Different Scales

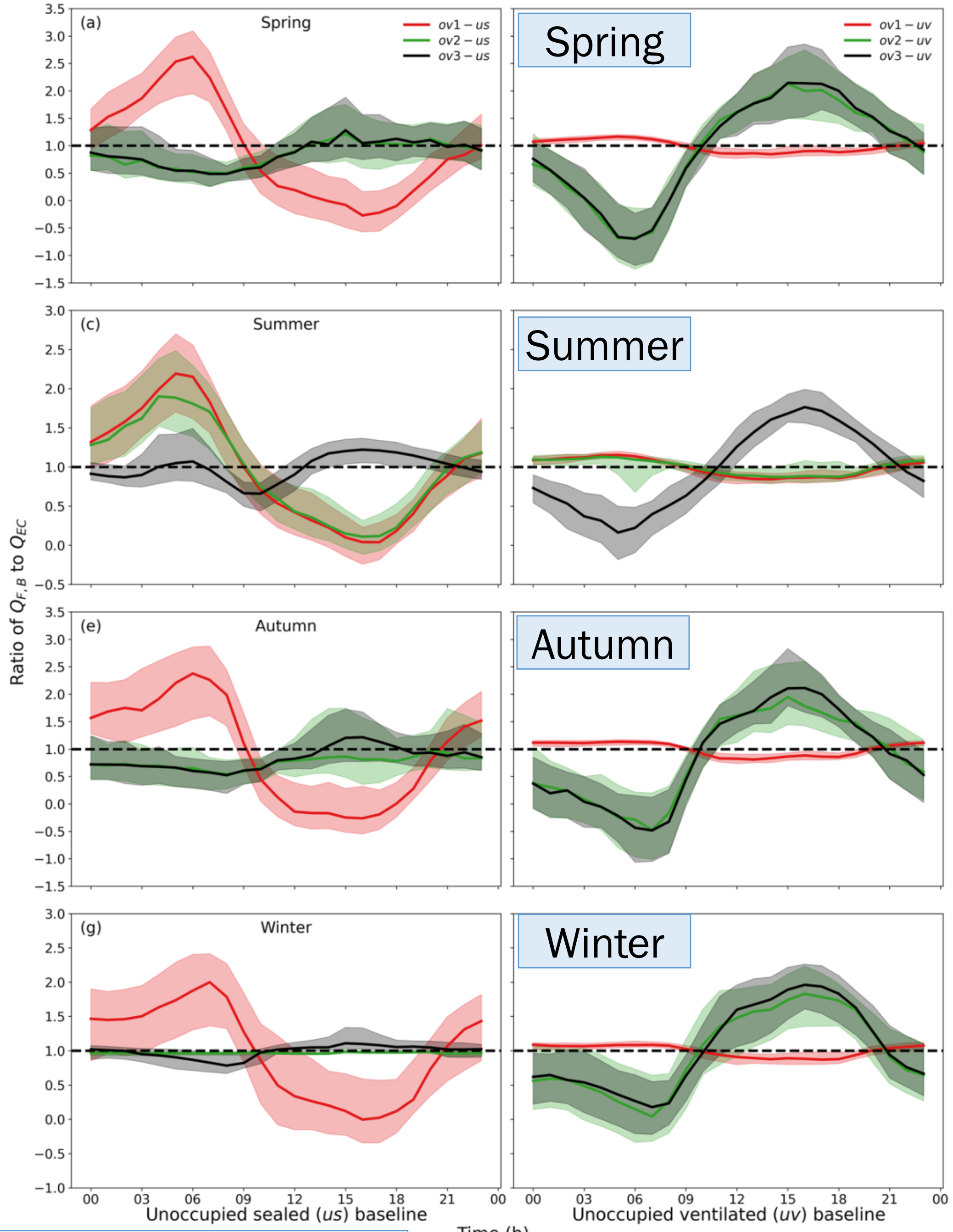
- Building Scale $Q_{F,B}$
- Building Energy Consumption Q_{EC}

Code	Occupation state	Natural ventilation	$Q_{\mathrm{Internal,\,o}}$ ($\mathrm{W\,m^{-2}}$)	Window open Temperature control (°C)	HVAC Heati[…] cooling setpoint (°[…]
us	uo	Sealed	0	n/a*	n
uv	uo	Window always open (50 %)	0	n/a*	n
ov_1	o	Window always open (50 %)	11.8	n/a*	n
ov_2	o	Controlled ventilation	11.8	23	n
ov_3	o	Mixed mode control	11.8	23	18.

Neighbourhood scale – People's Activity: Agent Based Modelling



Capel-Timms et al.: 2020 *Geosci. Model Dev.* 13, 4891–4924, https://doi.org/10.5194/gmd-13-4891-2020



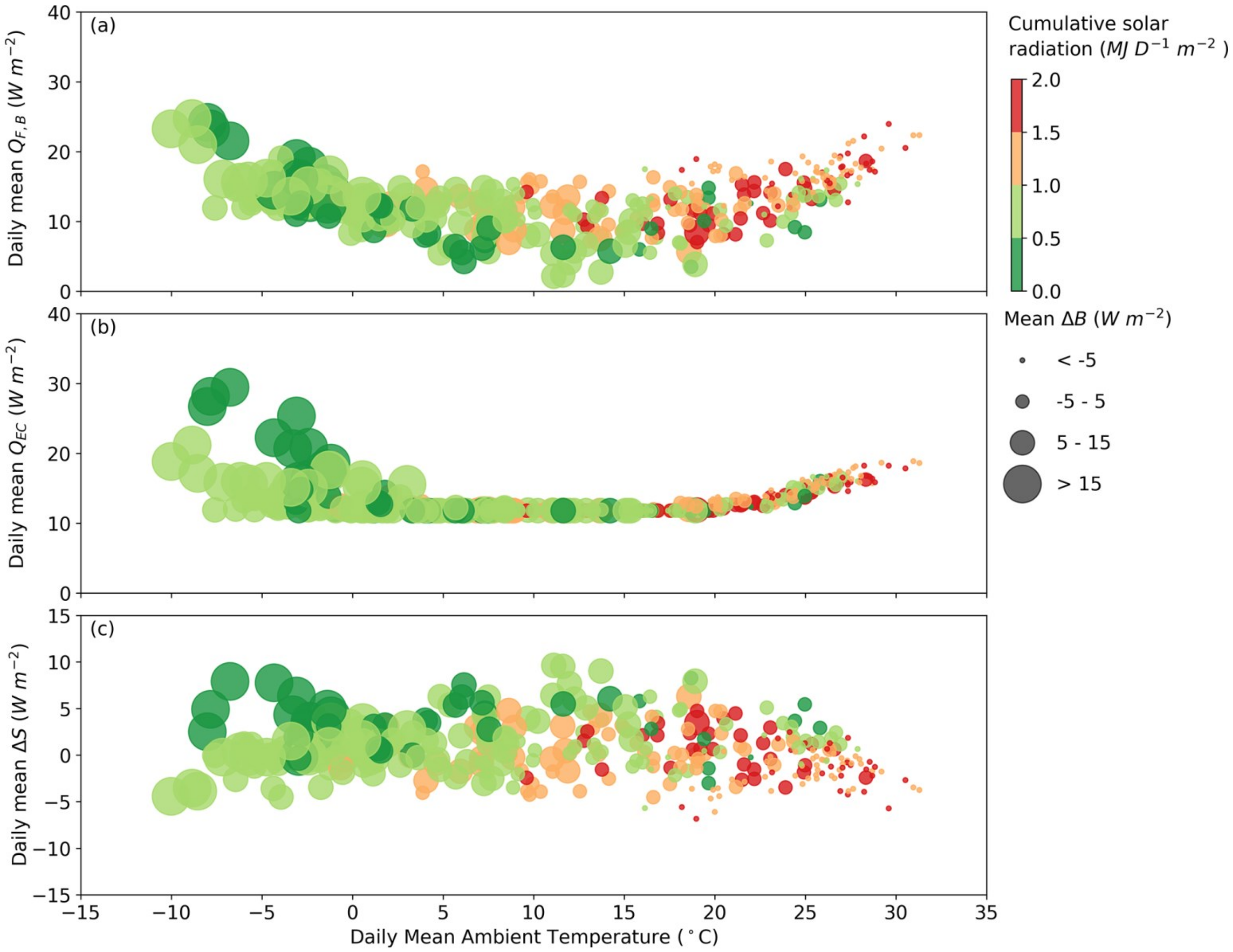
Liu et al. 2022: *Atmos. Chem. Phys.* https://doi.org/10.5194/acp-22-4721-2022

Daily Mean

Building $Q_{F,B}$

Building Energy Consumption Q_{EC}

Change in Storage Heat Flux ΔS



Total Solar Radiation

Available Energy

$$\Delta B_{\text{o-uo}} = [Q_{\text{Internal, o}} + Q_{\text{HVAC, o}}] - [Q_{\text{Waste, o}} + \Delta \text{BAE}_{\text{o-uo}}]$$

Air Temperature

Final Comments

- 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

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

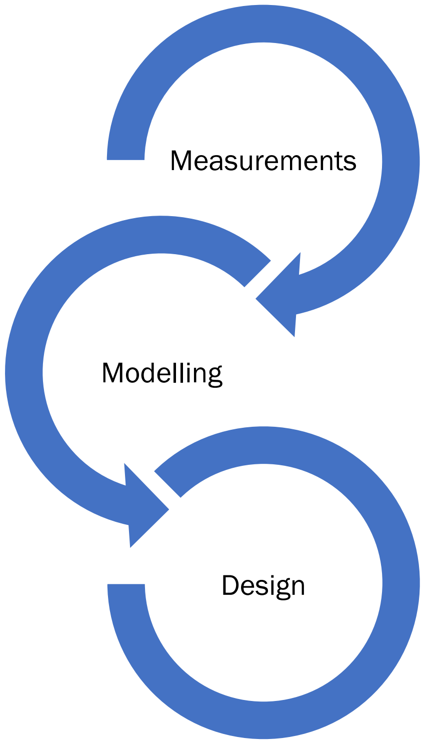
- A range of models are needed for a wide range of purposes

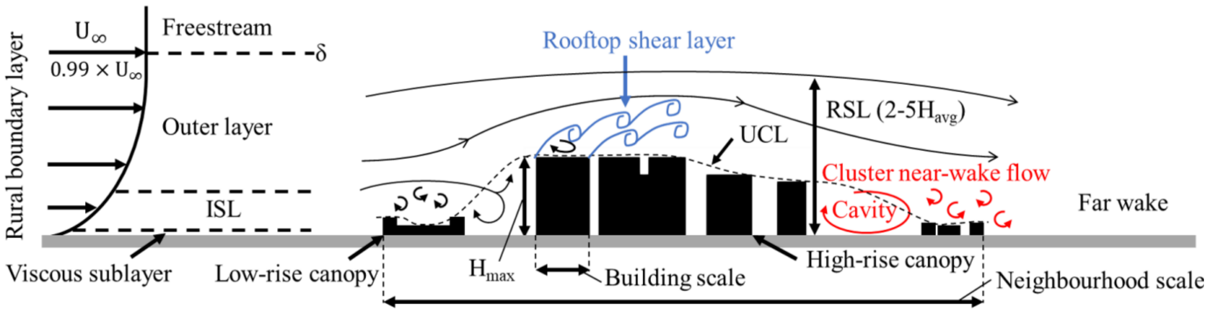
→ Improve weather or climate forecasts, assess impacts of proposed scenarios

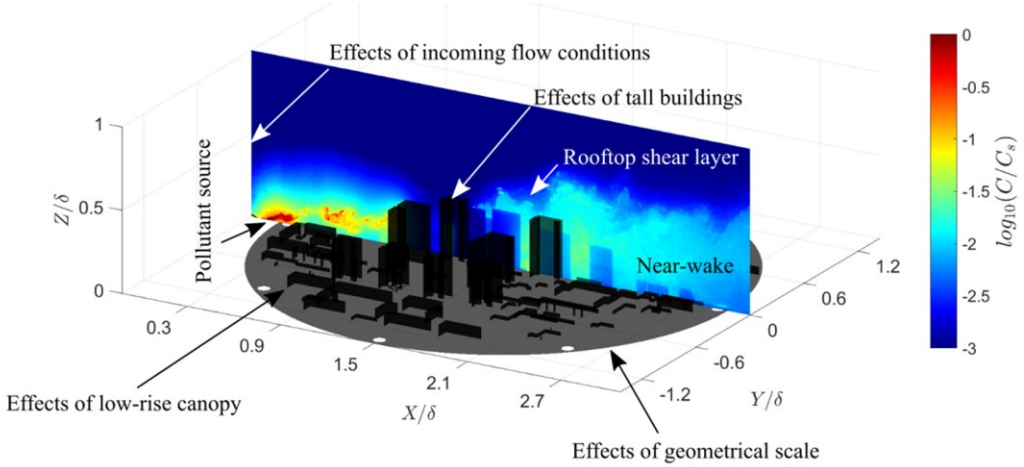
→ Improve building design

→ Reduce unnecessary energy use, reduce CO_2 emissions

→ Improve CO_2 modelling in urban areas, assess







Lim et al. 2022: *Experiments in Fluids* 63:92 https://doi.org/10.1007/s00348-022-03439-0

Most references available at:

- https://research.reading.ac.uk/meteorology/people/sue-grimmond/

- High Impact weather events shown (SLIDE 4):

- **Urban Floods**: Referendum Day UK (June 2016)
- **Wildfire:** Fort McMurray (May 2016, destroying ~2,400 homes and buildings)
- **Extreme Local Wind:** Storm Katie (March 2016) flights cancelled, property damaged and thousands without power.
- **Disruptive Winter Weather:** Storm Jonas (January 2016) Shut NYC and Washington
- **Urban Heat Waves & Air Pollution**: Kolkata (April 2016)

Photos Sources:

- www.bbc.co.uk/news/uk-england-35909651
- commons.wikimedia.org/wiki/Category:2016_Fort_McMurray_wildfire#/media/File:2016_Fort_McMurray_wildfire_(2).jpg
- www.huffingtonpost.com/entry/winter-storm-jonas-aftermath-more-snow_us_56a63d3be4b0404eb8f23376
- www.wmo.int/pages/prog/arep/wwrp/new/documents/Workshop_HIWeather_introduction.pdf
- http://i.amz.mshcdn.com/kJqlXX2gbqFh5Y2-NlULy8zrSZQ=/fit-in/1440x1000/http%3A%2F%2Fmashable.com%2Fwp-content%2Fgallery%2Fheat-wave%2F0013.jpg
- https://www.independent.co.uk/uk/home-news/uk-weather-london-flooding-floods-south-east-pictures-forecast-a7097316.html#

- https://ourworldindata.org/urbanization#what-share-of-people-will-live-in-urban-areas-in-the-futu