Centre for Earth Observation Instrumentation:
Thermal Remote Sensing Workshop
Leicester
4 December 2024

Applications of thermal remote sensing:

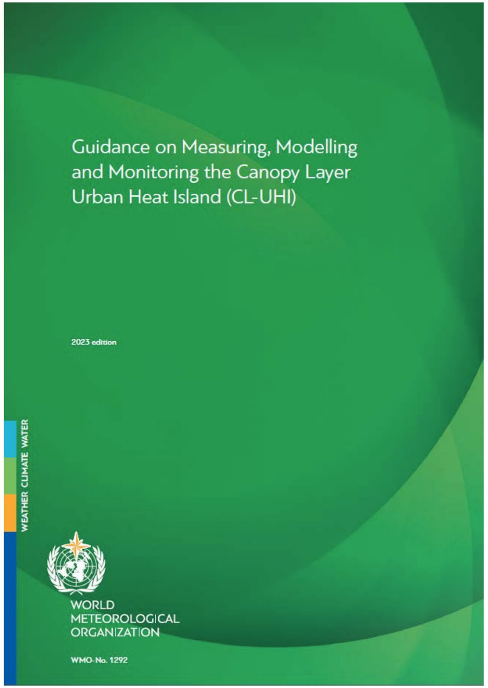
Urban

Sue Grimmond

Department of Meteorology, University of Reading, UK

References

Author (et al.)	YYYY	https://doi.org/
Fenner	2024	10.1175/BAMS-D-23-0030.1
Hall	2024	10.1002/qj.4669
Hang	2022	10.1016/j.buildenv.2022.109618
Hertwig	2024	GD - minor revisions
Kotthaus	2014	[10.1016/j.isprsjprs.2014.05.005](https://doi.org/10.1016/j.isprsjprs.2014.05.005)
Lipson	2022	[10.5194/essd-14-5157-2022](https://doi.org/10.5194/essd-14-5157-2022)
Lipson	2024	10.1002/qj.4589
Liu	2022	10.5194/acp-22-4721-2022
Liu	2024	10.1016/j.enbuild.2024.114668
Morrison	2018	10.1016/j.rse.2018.05.004
Morrison	2020	10.1016/j.rse.2019.111524
Morrsion	2021	10.1016/j.uclim.2020.100748
Morrison	2023	10.1016/j.rse.2019.111524
Oke	2017	***Urban Climates***, Cambridge Univ. Press
Stretton	2023	10.5194/gmd-16-5931-2023
WMO	2023	WMO-No. 1292 https://library.wmo.int/idurl/4/58410
Wu	2024	10.1016/j.rse.2024.114003
Xie	2022	10.1016/j.buildenv.2021.108628



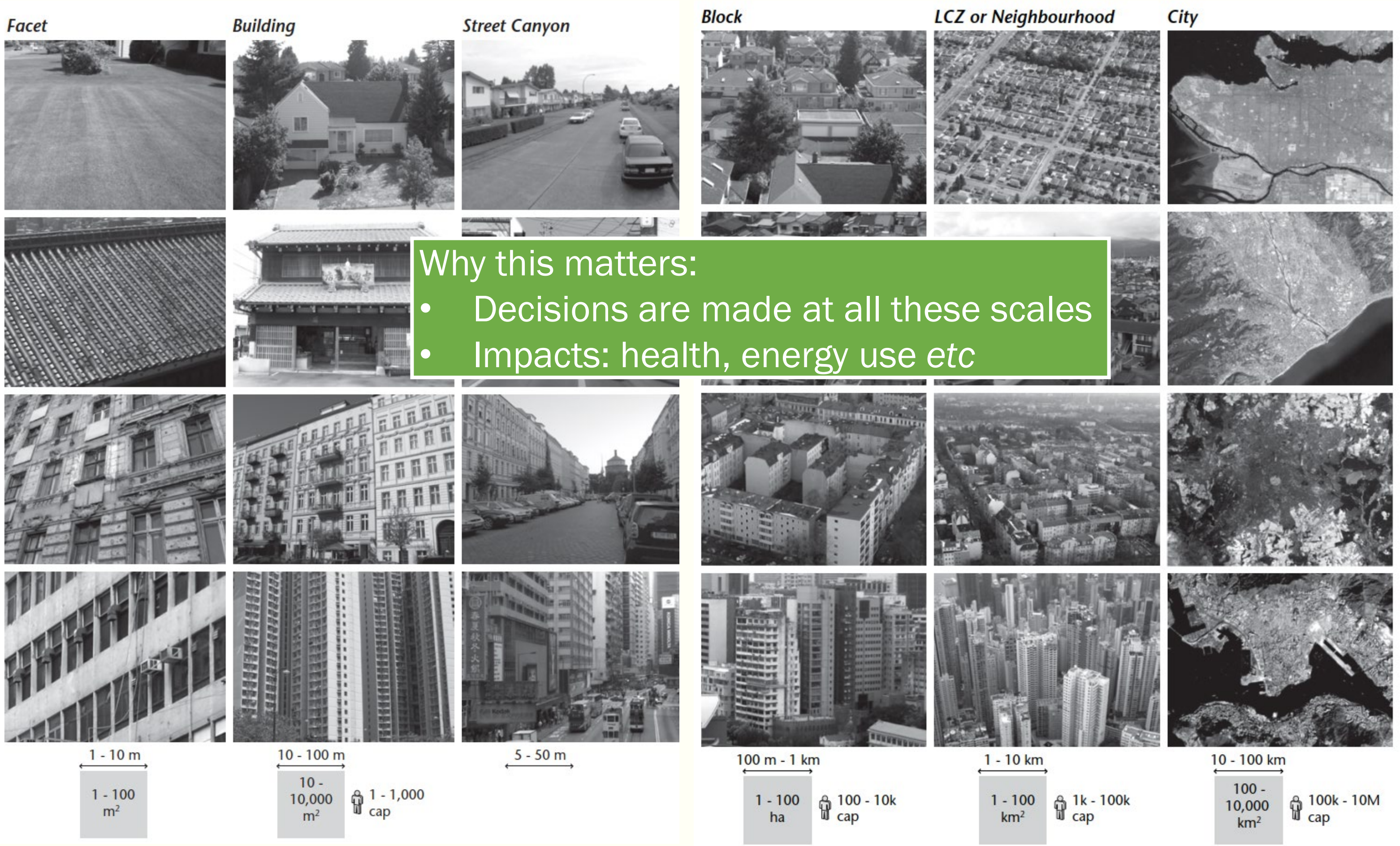
Challenges of the urban environment

- Scale of the urban form
- Viewing the facets of the urban
- Variability of the urban form
- Urban materials
- Urban activities

- Complexity – these are combined and dynamic

- Applications

Scale of the urban form



Why this matters:

- Decisions are made at all these scales
- Impacts: health, energy use *etc*

Oke et al. 2017: Fig. 2.3

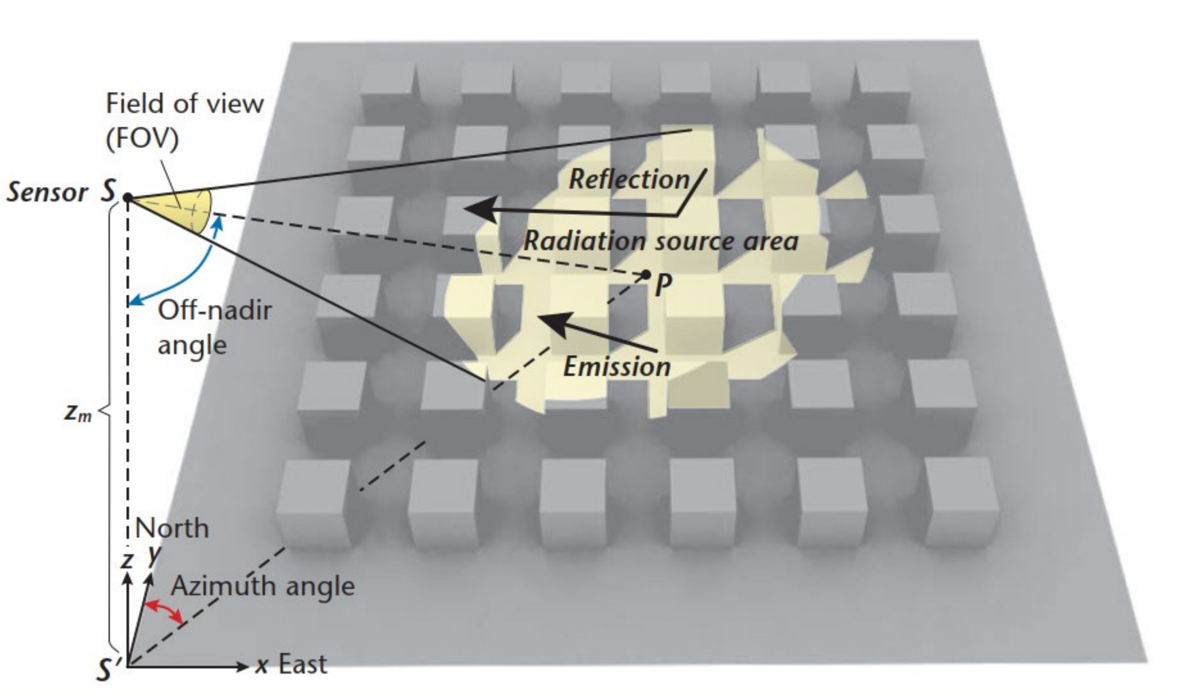
Scale and the urban form

- Satellite considerations relative to urban form

Spatial resolution Temporal Frequency	4-5 km < 1 h	100 m 10 - 14 days/ 1 time of day
Urban Feature		
City and surroundings	100 pixels	10000 pixels
Neighbourhood	1 – 20 /pixel	100 pixels
Block	10 -100 /pixel	10-20 pixels
Streets	10 -100 /pixel	1/pixel
Buildings	1000 /pixel	1-10/pixel
Facets	10000 /pixel	[10 /pixel]

Why this matters:
- Hard to get information at the right scale for many applications
- Need to think carefully about what a satellite/sensor is seeing relative to the application needs

Viewing the facets of the urban surface

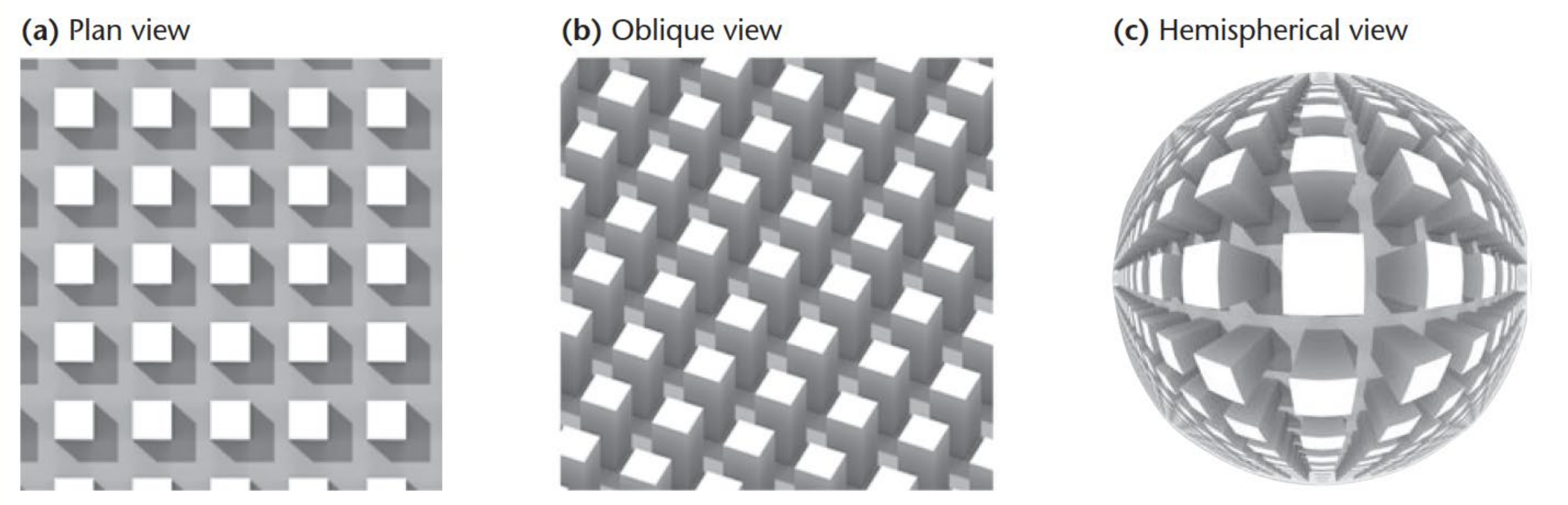


Why this matters:

- Nadir – roofs and streets seen
- Off-Nadir: some wall, roofs and some streets seen

Oke et al. 2017: Fig. 3.6

Viewing the facets of the urban surface

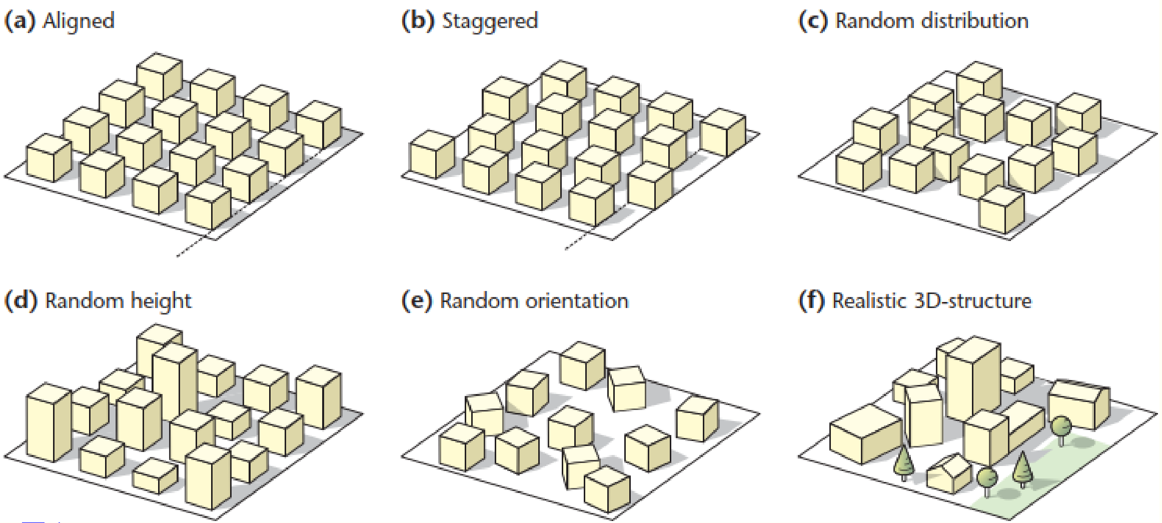


Why this matters:

- Nadir – roofs and streets seen
- Off-Nadir: some parts of some walls, roofs and some of parts streets
- Not seeing: all wall orientations, all parts of the wall
- Hemispherical view: small sample

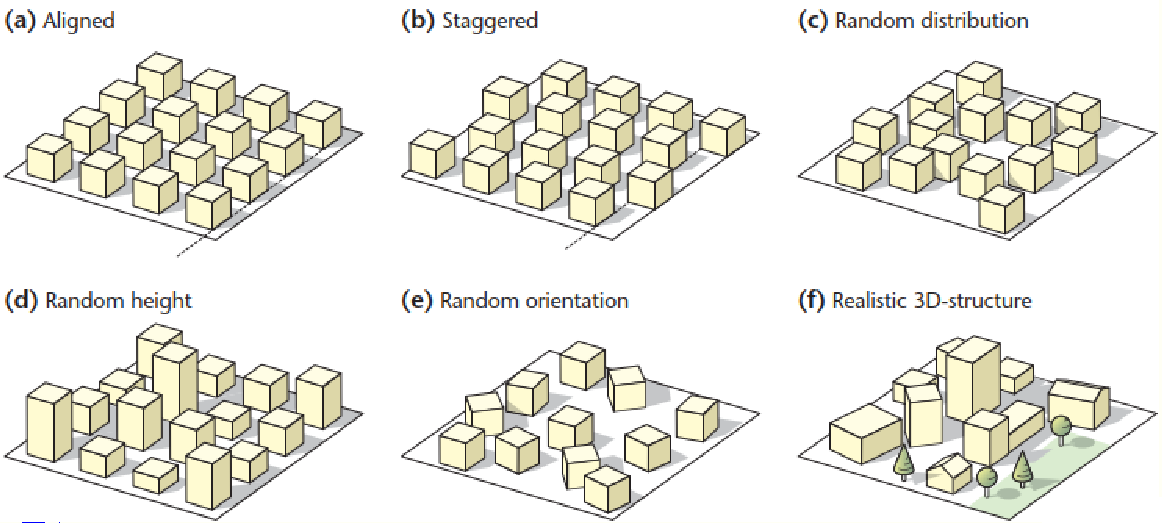
Oke et al. 2017: Fig. 3.5 Adderly et al. 2015

Variability of the urban form

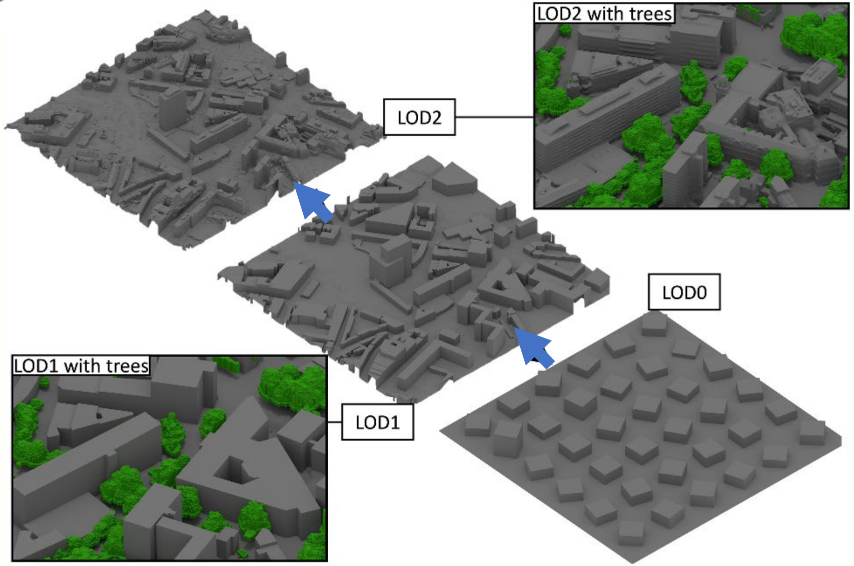


Oke et al. 2017: Fig. 2.8

Variability of the urban form



Why this matters:
- Cities are much more complex than cuboids



Oke et al. 2017: Fig. 2.8 | Morrison et al. 2023: RSE

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

Challenges of the urban environment

- Scale of the urban form
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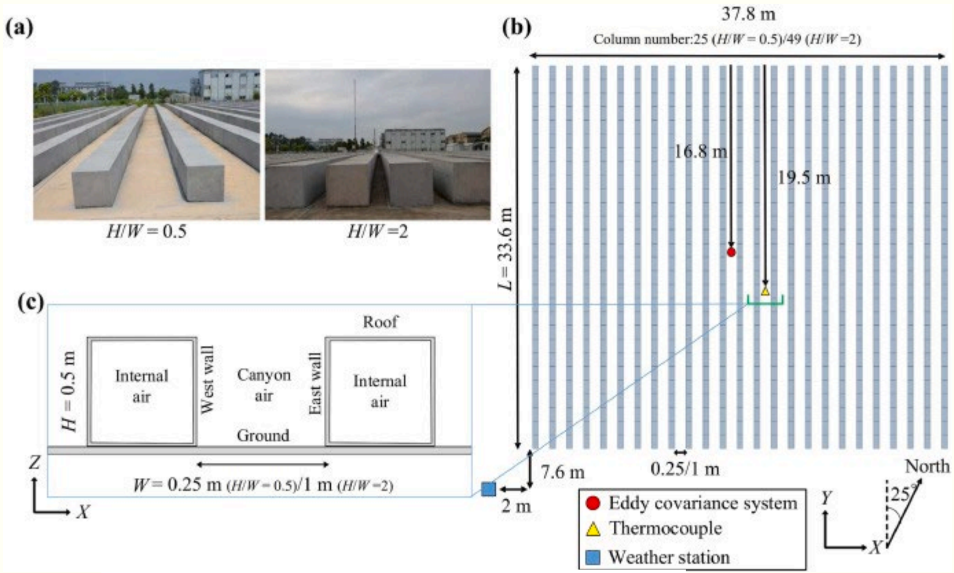
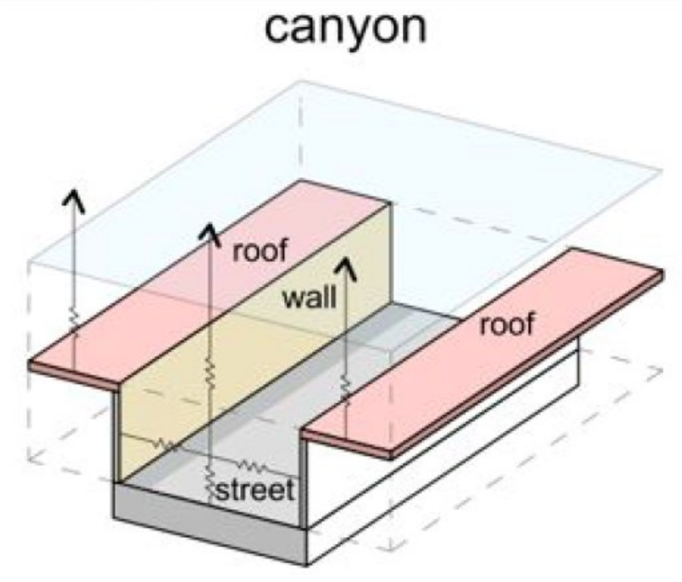
- Variability of the urban form
- Urban materials
- Urban activities

- Complexity – these are combined and dynamic

Simple urban form: the urban canyon - constant materials



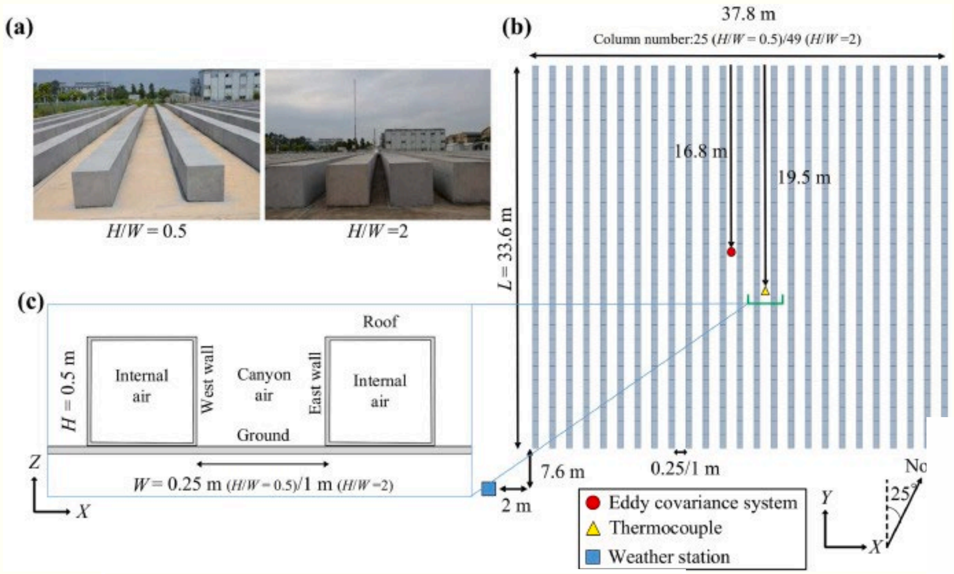
SOMUCH – urban canyons
0.5 m – concrete
H:W of 0.5 and 2



- Planar facets
- 1 value per facet

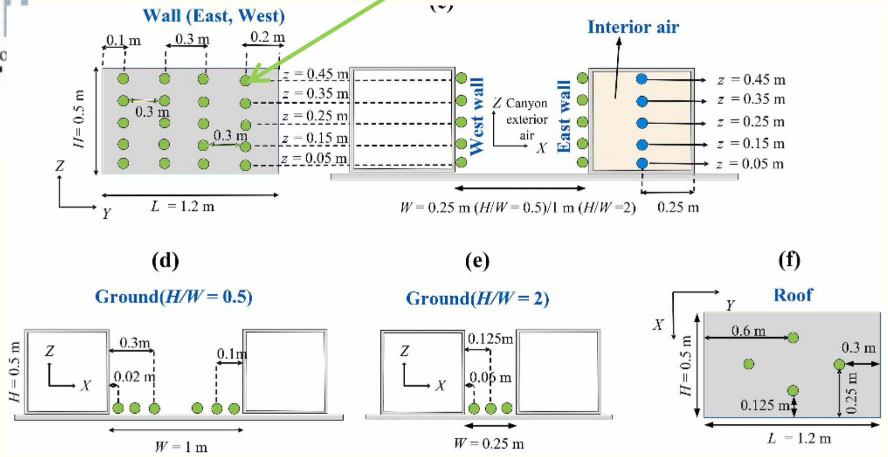
Hang *et al*. 2022 BE | Lipson *et al.* 2024 QJRMS

Simple urban form: the urban canyon - constant materials



SOMUCH – urban canyons
0.5 m – concrete
H:W of 0.5 and 2

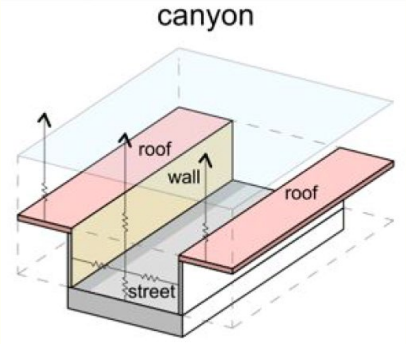
Thermocouples – attached to the surface facets



Hang *et al*. 2022 BE | Lipson *et al*. 2024 QJRMS

Simple urban form: constant materials

H/W =2



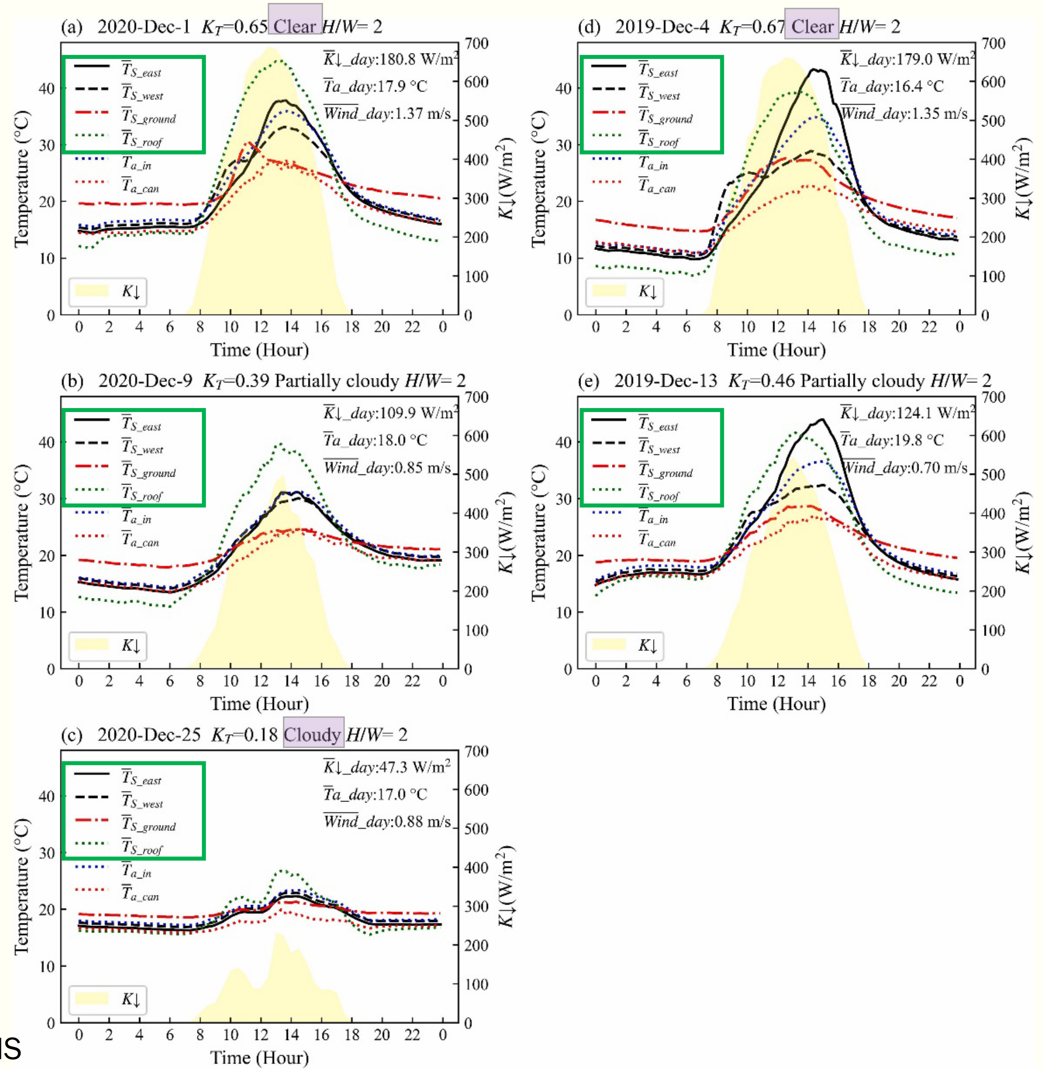
SOMUCH – urban canyons

0.5 m – concrete

H/W = 2

Facet T- average of

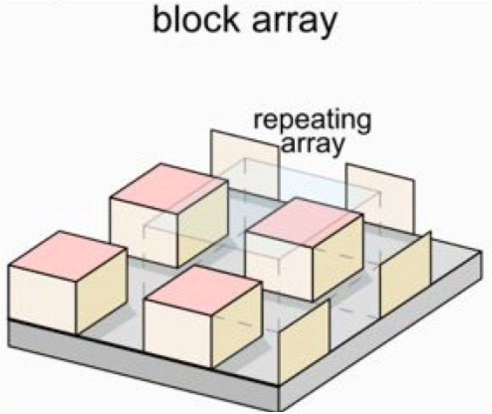
Thermocouples points



Hang *et al*. 2022 BE | Lipson *et al*. 2024 QJRMS

Simple urban form: constant materials

COSMO: Aligned Cubes
1.5 m - concrete



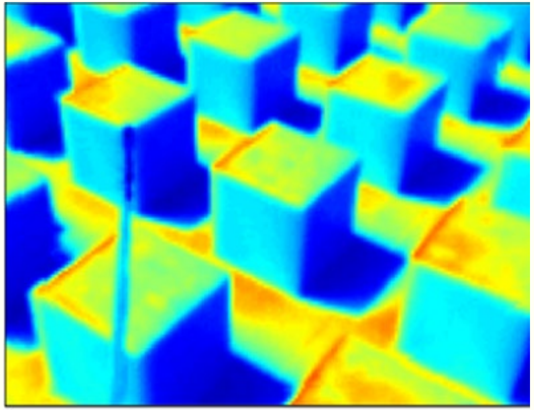
Cubes: coloured by facet

Morrison *et al*. 2018 RSE | Lipson *et al.* 2024 QJRMS

Simple urban form: constant materials

Cubes: coloured by facet

COSMO: Aligned Cubes
1.5 m - concrete



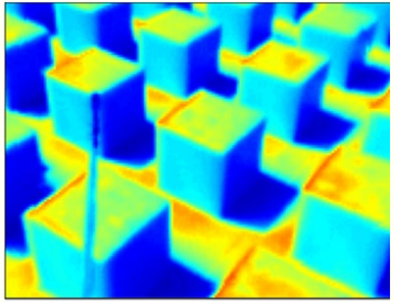
Brightness Temperature,
thermal camera

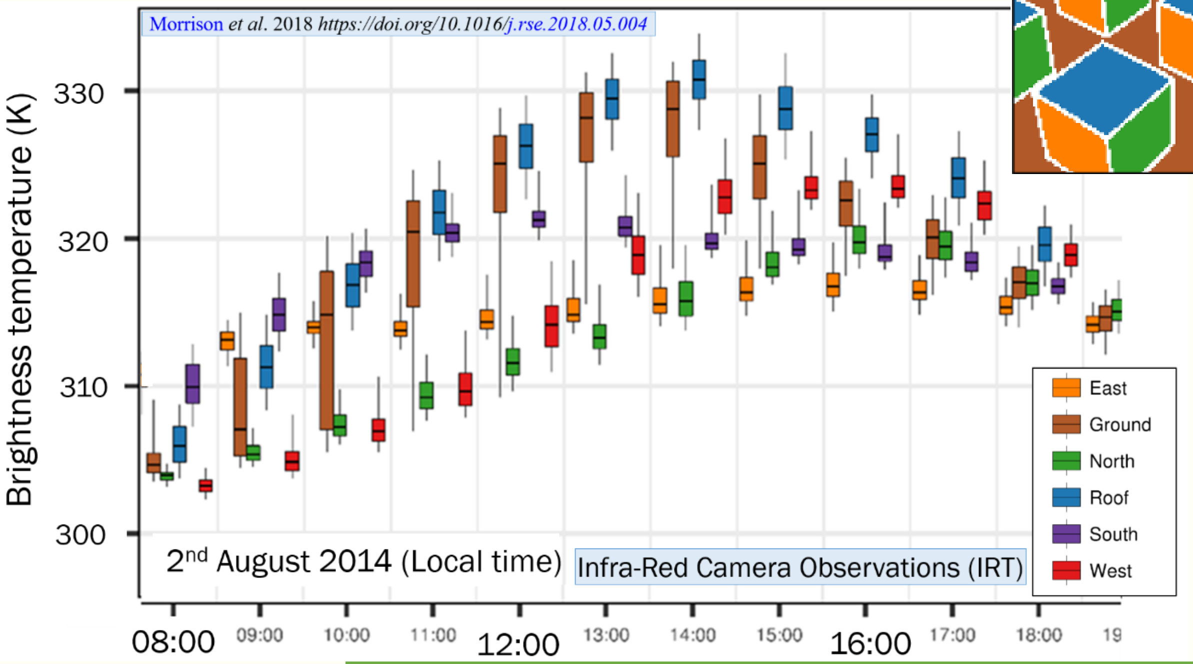
Morrison *et al*. 2018 RSE | Lipson *et al.* 2024 QJRMS

Simple urban form: constant materials

COSMO: Aligned Cubes
1.5 m - concrete

Brightness Temperature, thermal camera



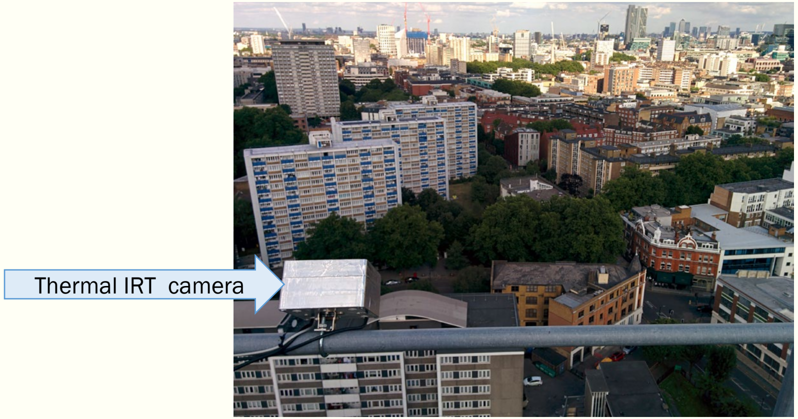


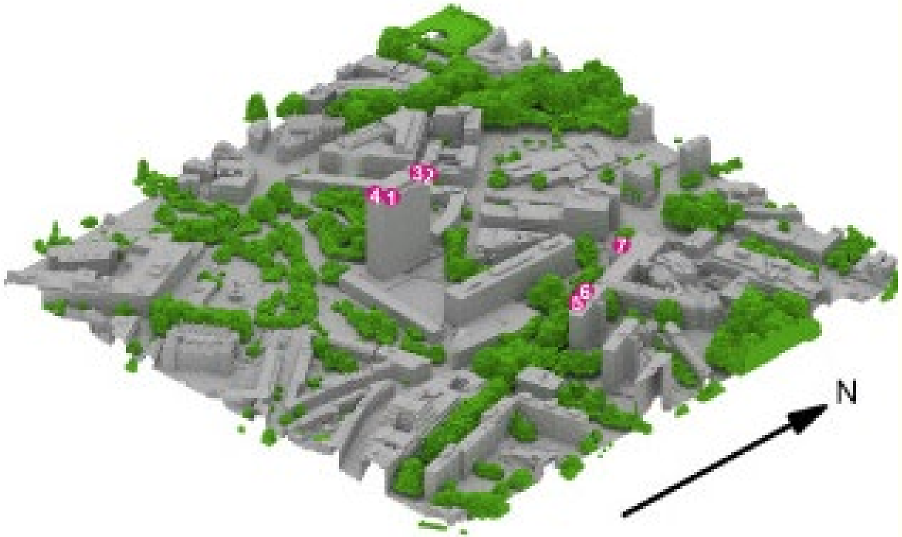
Cubes: coloured by facet

- Brightness temperatures differ by > 30 K
- Ground highly variable from shadows
- *Morning:* most variability
- *Afternoon*: more isothermal

Morrison *et al*. 2018 RSE

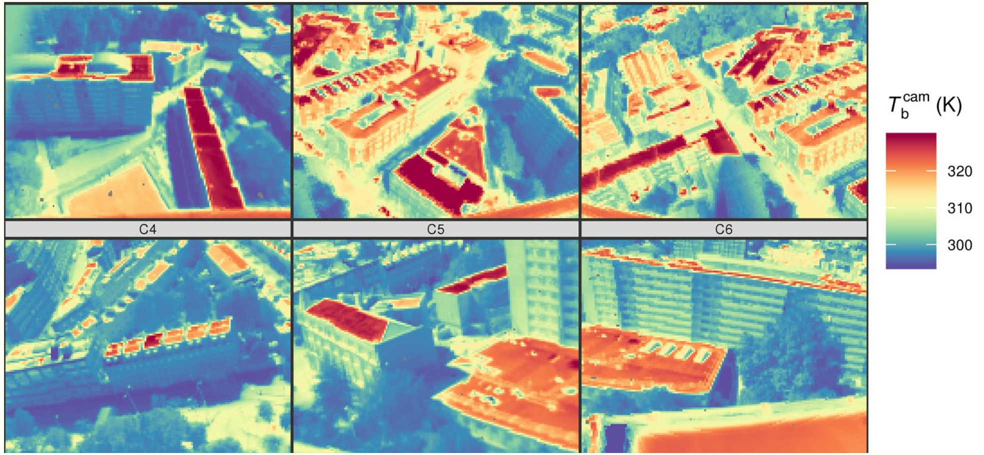
Surface Temperature: London

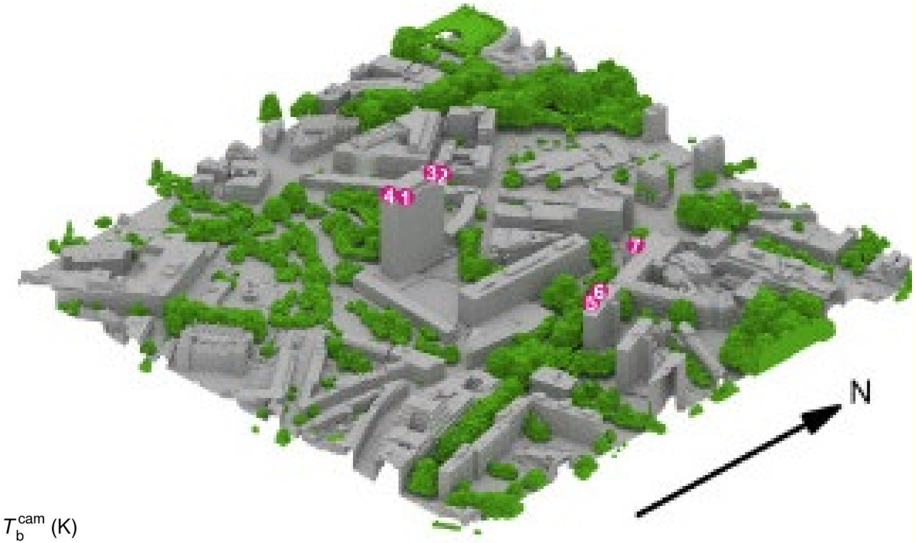




Morrison et al. 2020 RSE

Surface Temperature: London

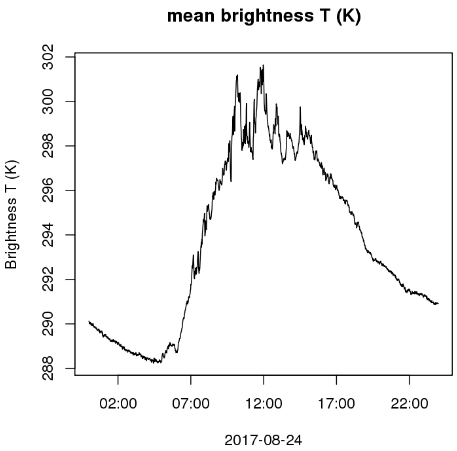


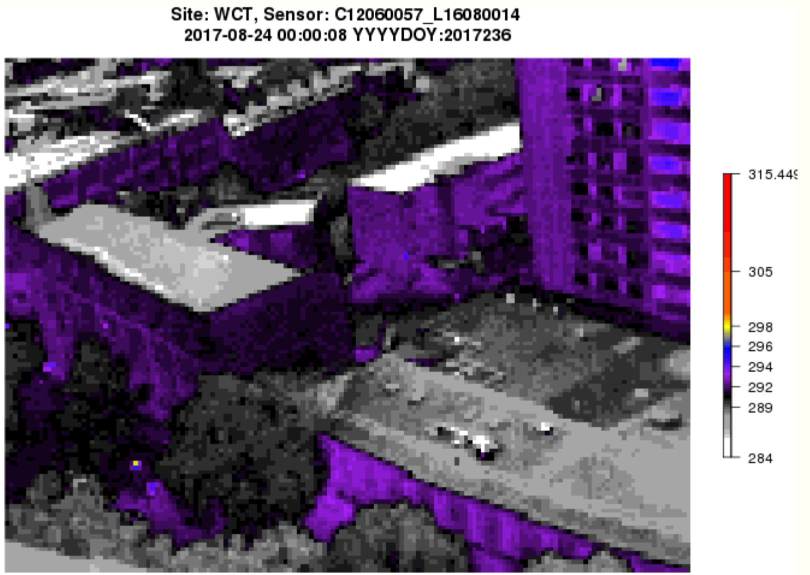


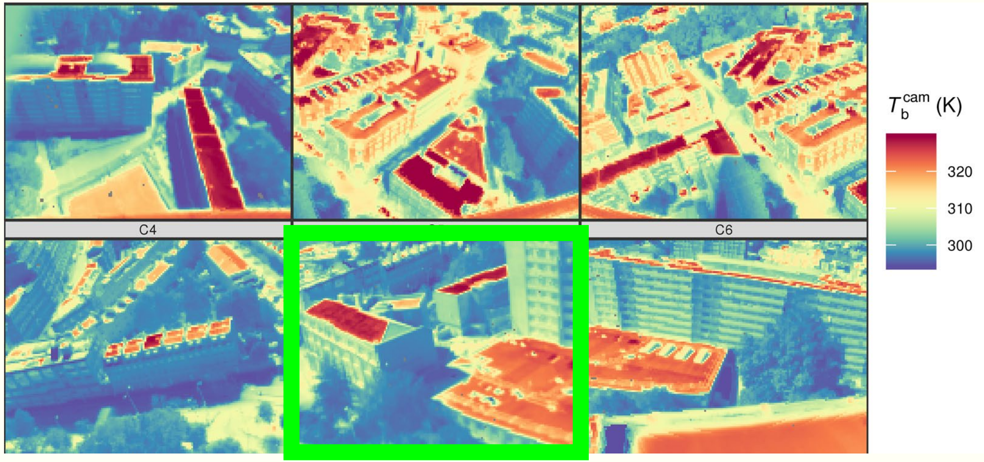
27 August 2017

Morrison et al. 2020 RSE

Inter & intra-material differences





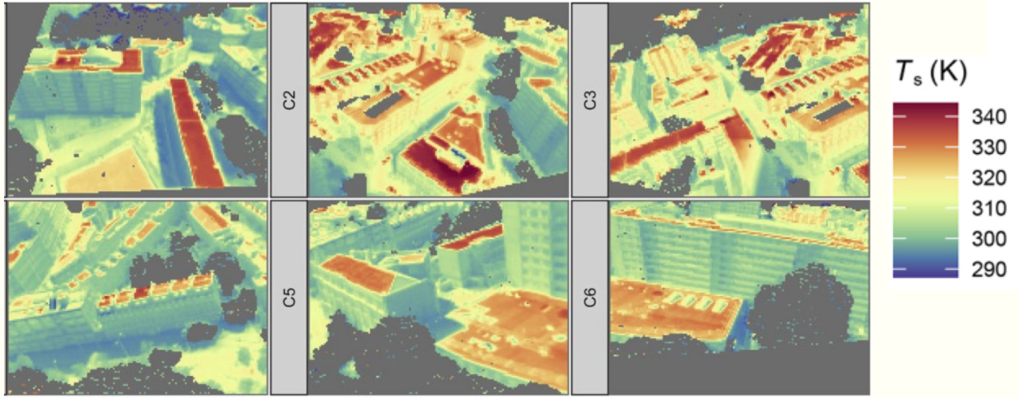


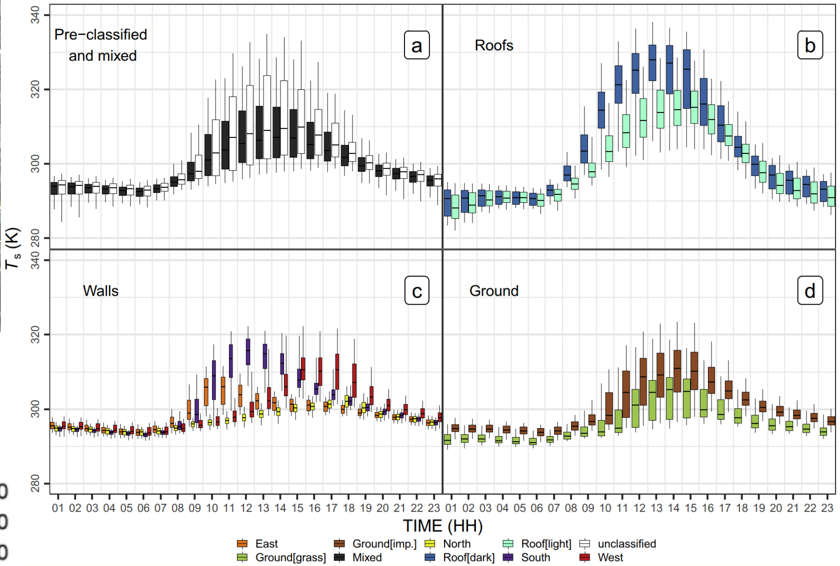
Morrison et al. 2020 RSE

Surface Temperatures: spatial and temporal variability

central London

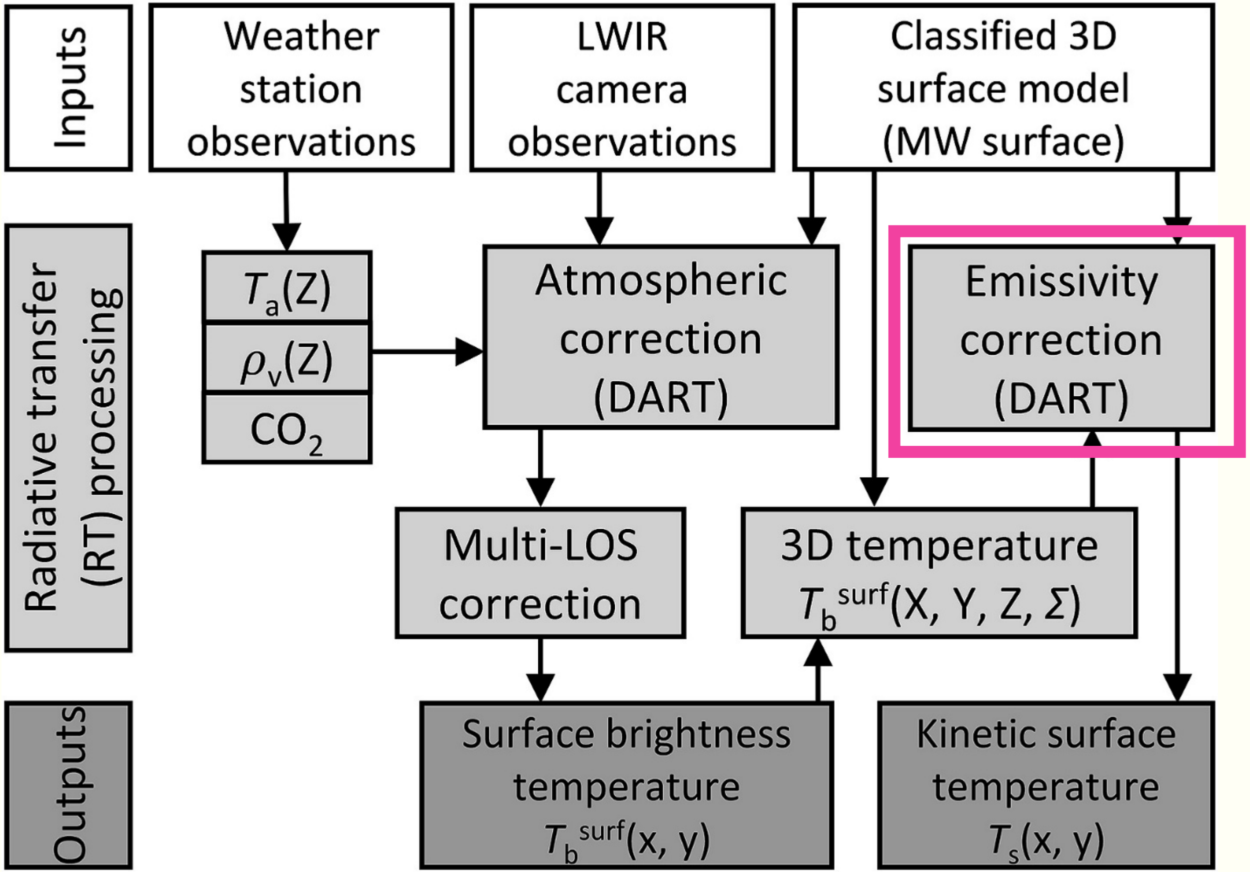
Observations: Infra-red thermal camera, combined with DART (3D model)





Morrison et al. 2021 *Urban Climate* | Morrison et al. 2020 RSE

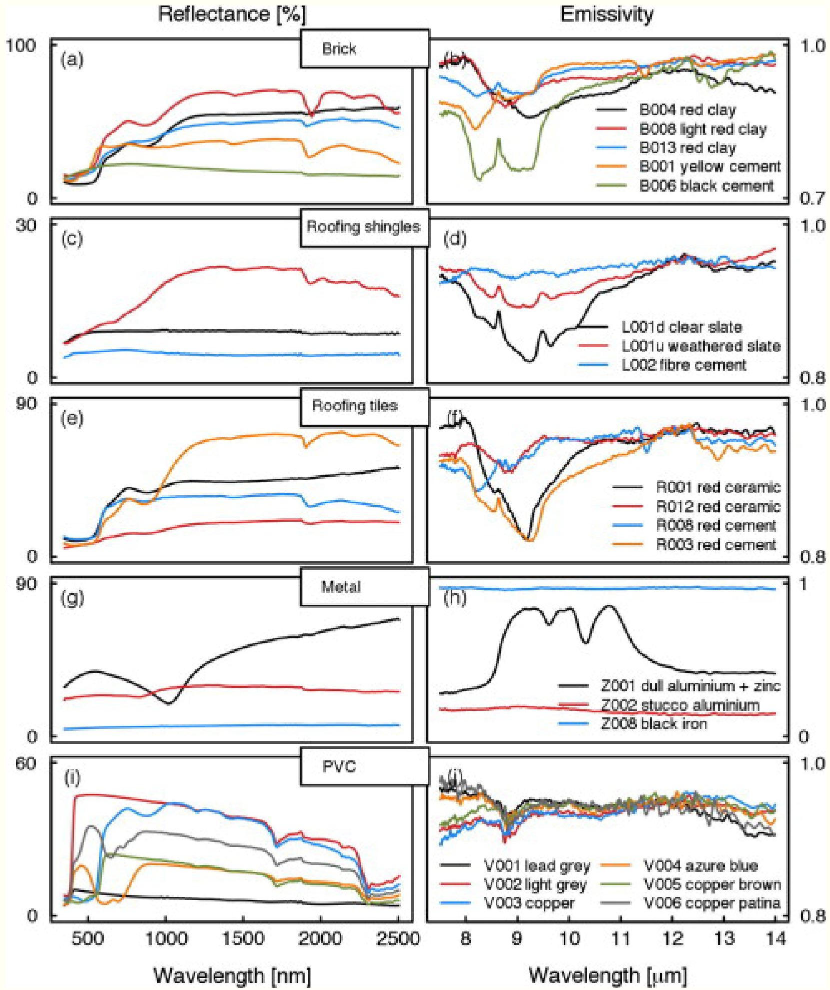
Corrections



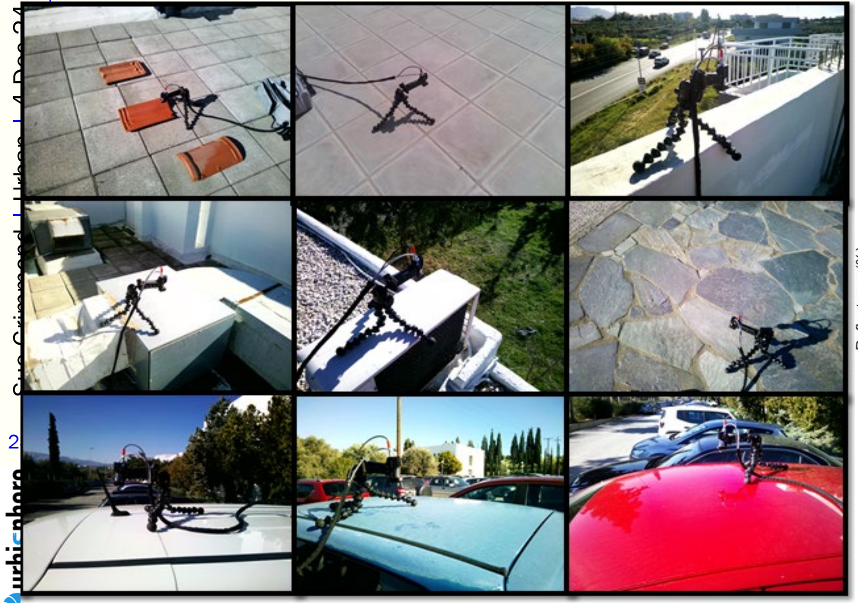
Morrison et al. 2020 RSE

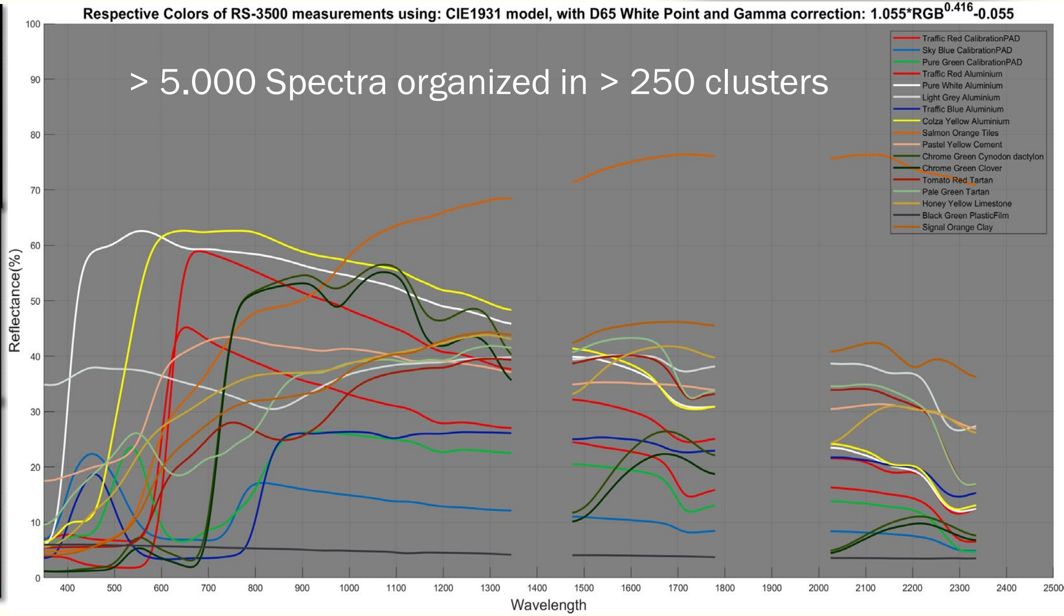
Spectral Library

- Materials
- What are present
  - Radiative properties
- Emissivity corrections



Kotthaus et al. 2014 ISPRS-JPPRS

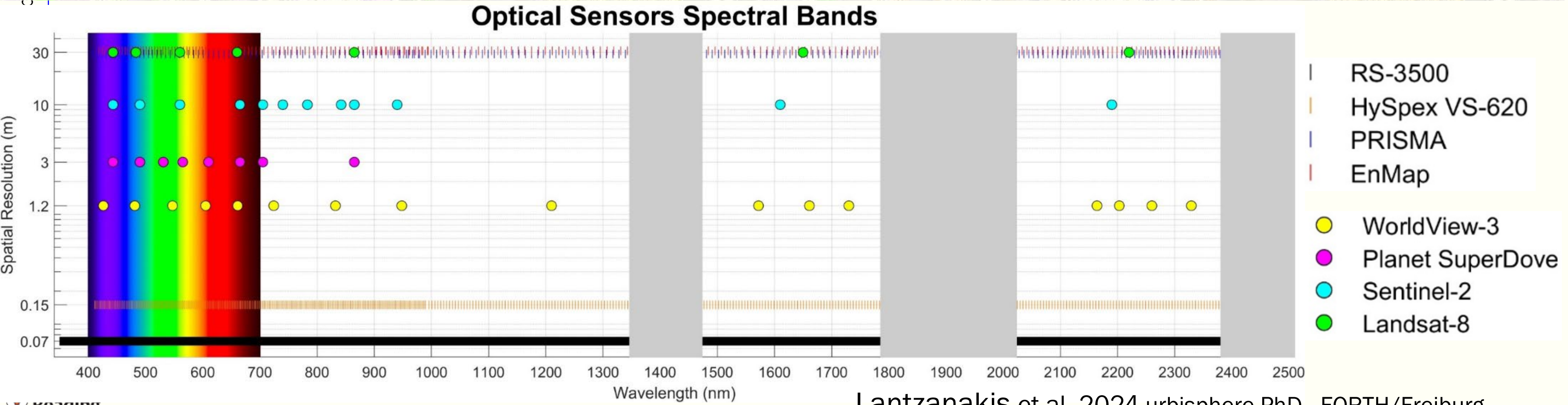




http://rslab.gr/hypersamples.html

Lantzanakis et al. 2024 urbisphere PhD - FORTH/Freiburg

Identifying materials



Lantzanakis et al. 2024 urbisphere PhD - FORTH/Freiburg

Challenges of the urban environment

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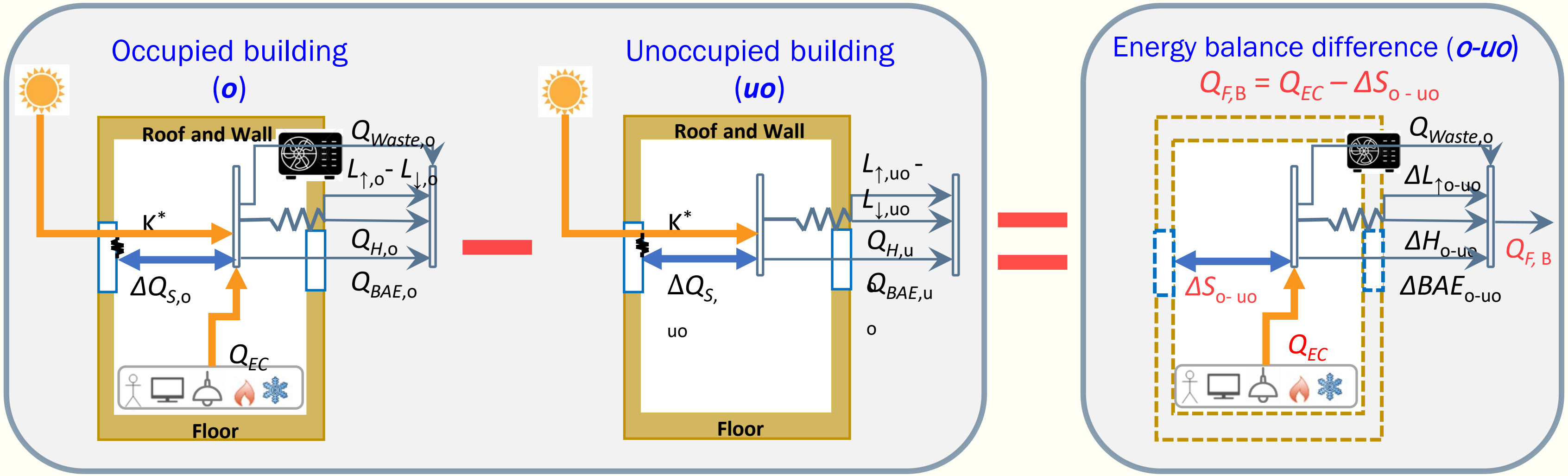
- Complexity – these are combined and dynamic

Building energy modelling: $Q_{F,B}$ from building physics

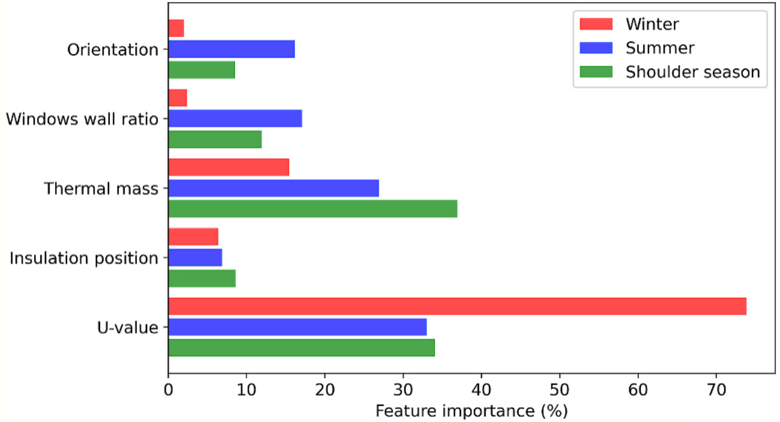


K^*	New shortwave radiation	o	Occupied building	$Q_{F,B}$	Anthropogenic heat flux from building
L	Longwave radiation	uo	Unoccupied building	Q_{EC}	Building energy consumption (including human metabolism)
Q_H	Turbulent sensible heat	↑	Outgoing	ΔS	Change in heat storage flux induced by human activities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

Liu et al. 2022: *Atmospheric Chemistry and Physics*

Importance of building parameters on $Q_{F,B}$

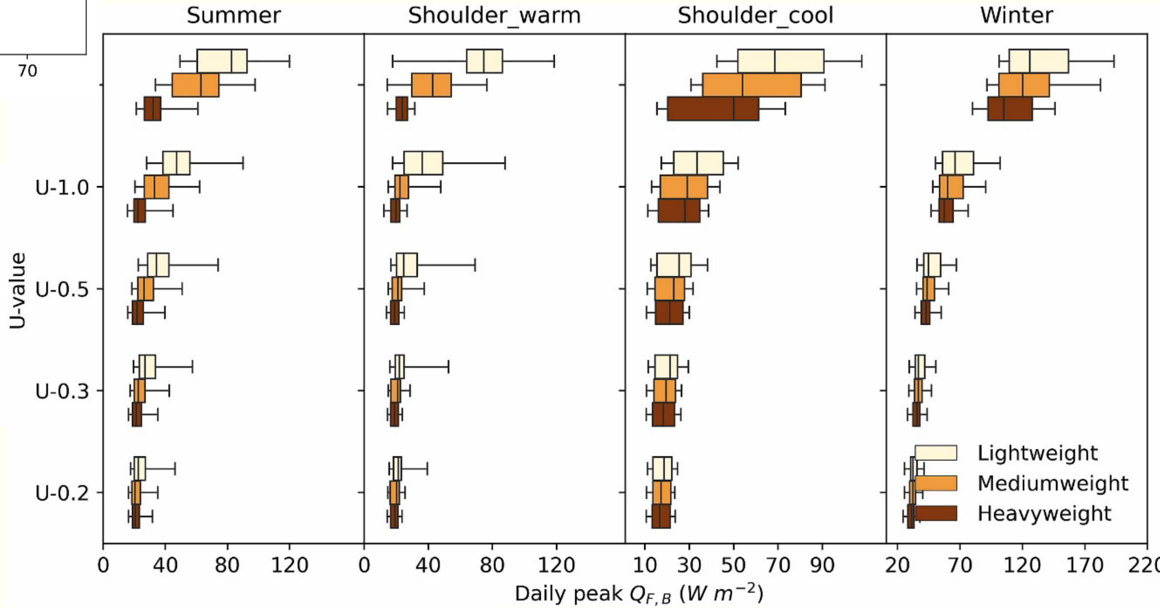
Beijing TMY



Relative importance of building parameters on $Q_{F,B}$ diurnal patterns for different seasons

Parameter types and values used in simulations (600 cases).

Parameters	Units	Discrete values used
Windows orientation	°	0, 90, 180, 270
Windows wall ratio	%	10, 20, 30, 40, 50
Thermal mass	kJ m^{-2} K^{-1}	Heavyweight (404.5), mediumweight (148.5), lightweight (96.0)
Insulation position	–	External, internal
Thermal transmittance (U-value)	W m^{-2} K^{-1}	0.2, 0.3, 0.5, 1.0, 2.1



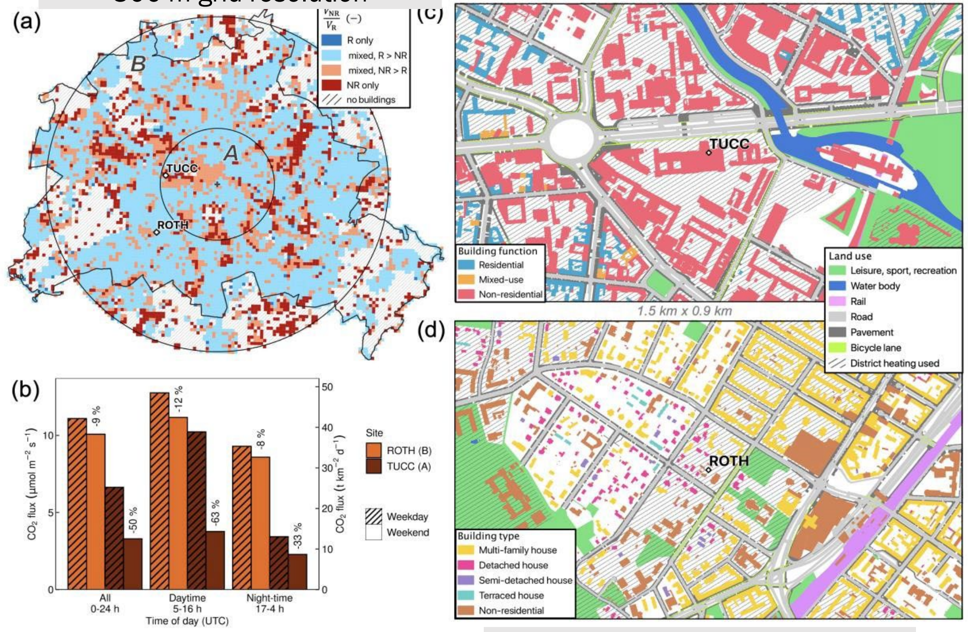
Liu et al. 2024: *Energy & Buildings*

Spatial and temporal variability of Form and Function

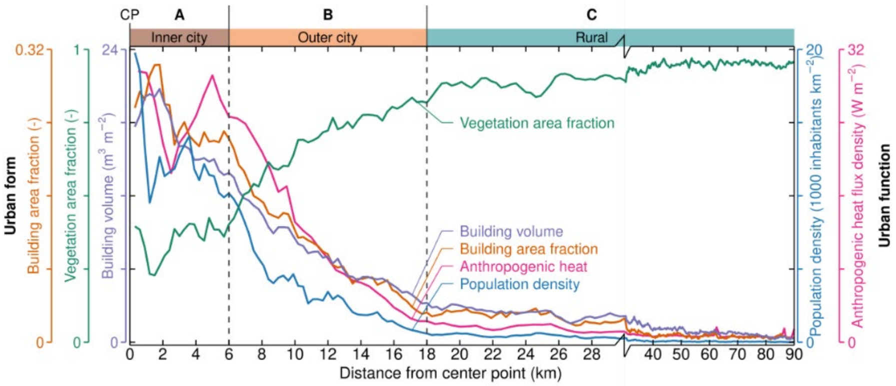
urbisphere-Berlin

Non-residential to residential
building volume V_{NR}/V_R
300 m grid resolution

Building function: TUCC



Residential building form: ROTH

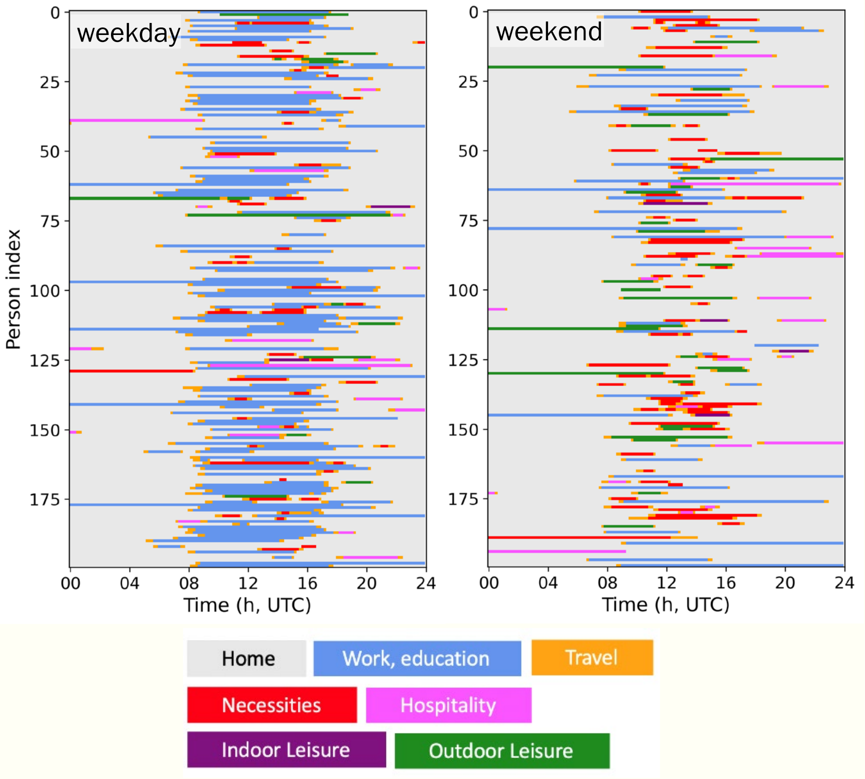


Winter CO_2 fluxes
TUCC A, ROTH B
weekdays & weekends

Fenner et al. 2024 BAMS

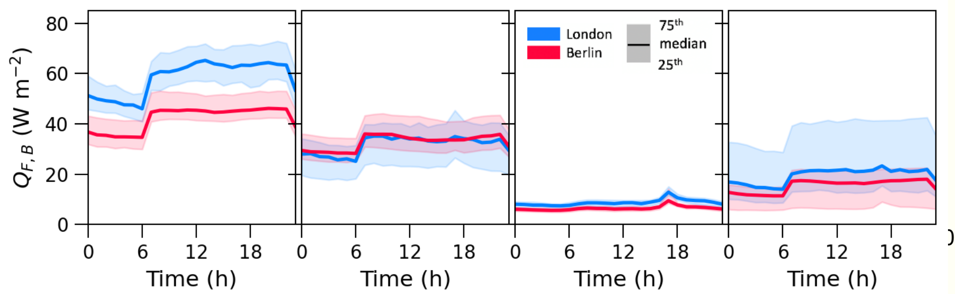
High-resolution, city-scale simulations of Q_F

- Time spent in microenvironments (including travel)



Anthropogenic heat emissions from buildings

Example: terraced house archetypes

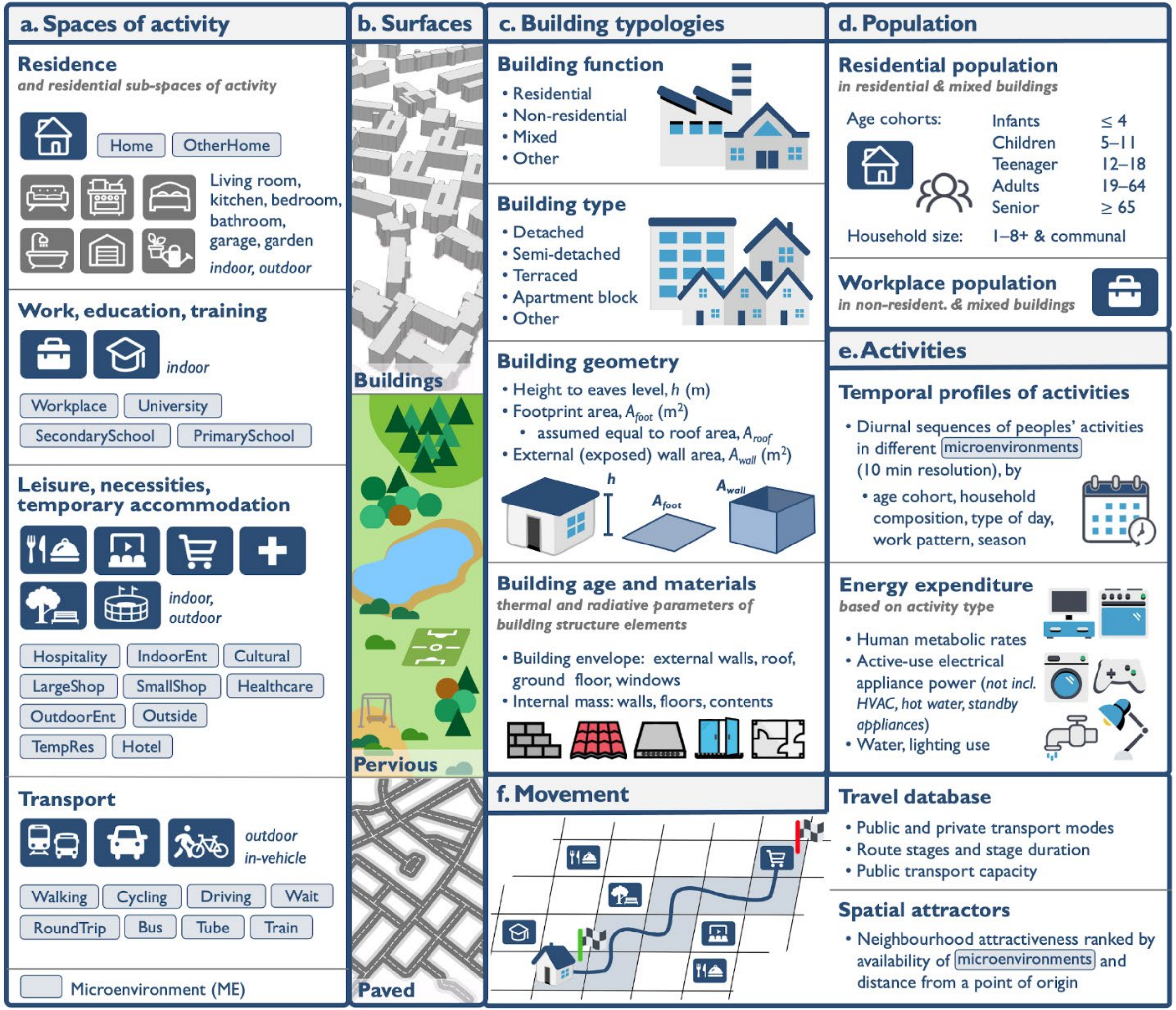


- Dynamic building occupancy and energy use
- Neighbourhood-level variability of building form (high-res. GIS data) and materials (via building age)

Hertwig et al. 2024 GD | Hertwig et al. in prep

Many aspects of cities vary

- Spaces of activity
- Land surfaces
- Building typologies
- Populations
- Activities
- Movement



Hertwig et al. 2024 *GD*

MAPSECC: London

- Where people are

Building energy: STEBBS

- typologies by function and type
- material properties
- household types by typologies

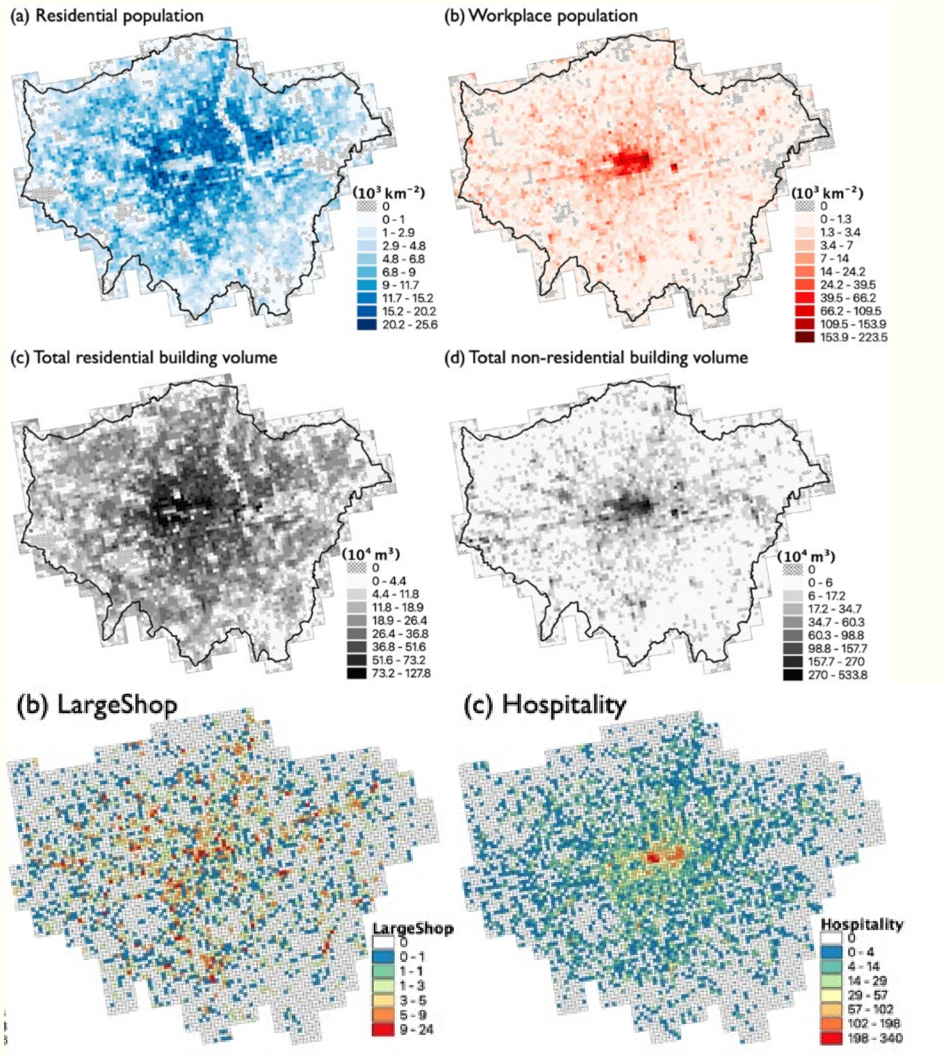
buildings

- Where different types of indoor activities occur

Behaviour: SHAPE

- population
- activity profiles
- energy expenditure

people



Hertwig et al. 2024 *GD*

Applications

- Urban Heat Island
- NWP – numerical weather prediction
    - Hall et al. evaluating LST @ 100 m NWP/Climate
- Urban canopy Modelling
    - Stretton evaluation of Radiation Modelling for NWP/Climate
- Building Energy modelling
    - Xie – impact on building energy use
- Complementing other field observations
    - urbisphere

Urban heat island (UHI) four types

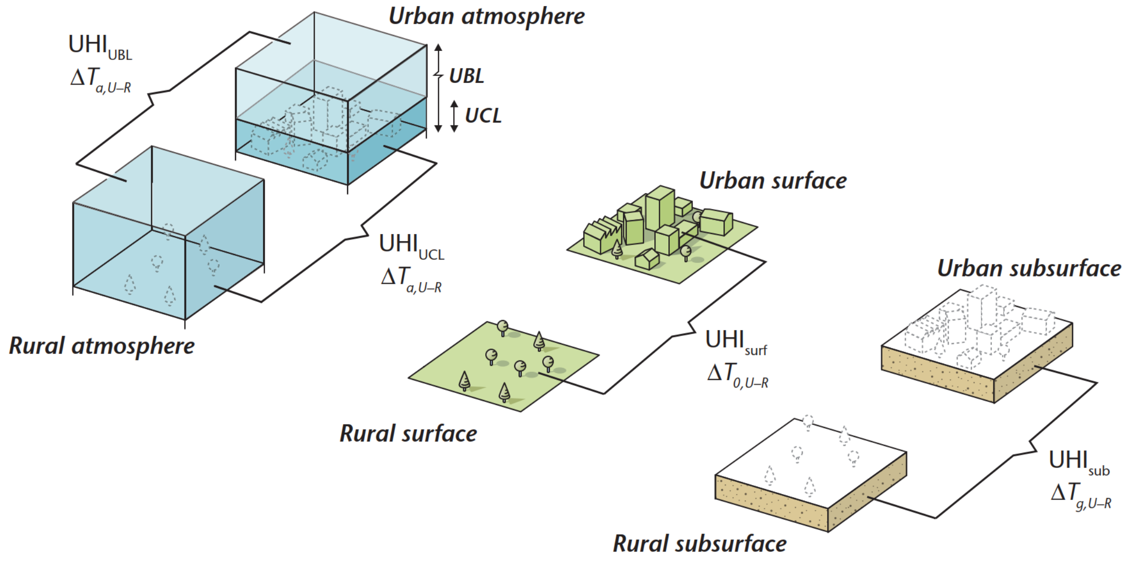


Figure 7.2 Illustration of the temperature differences forming the four types of UHI: in the UBL (air layer from the ground up to the entrainment zone), the UCL (air layer from ground to about roof level), the surface (the complete surface including ground and all exposed facets of urban elements), and the subsurface (ground surface to depth of active temperature change over period of interest).

Oke et al. 2017

What is the urban surface ?

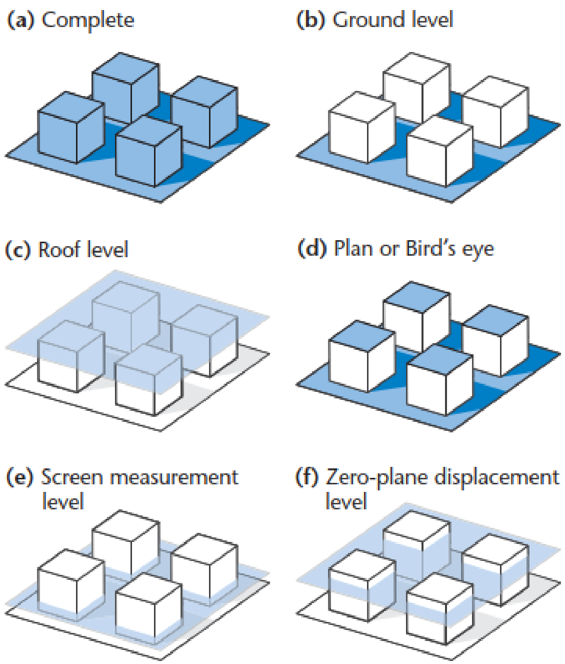


Figure 2.2 Potential definitions, or perspectives, of the 'surface' (in blue) of a highly simplified representation of an urban system.

Why this matters:

- Different applications want information about different aspects of the 'surface'

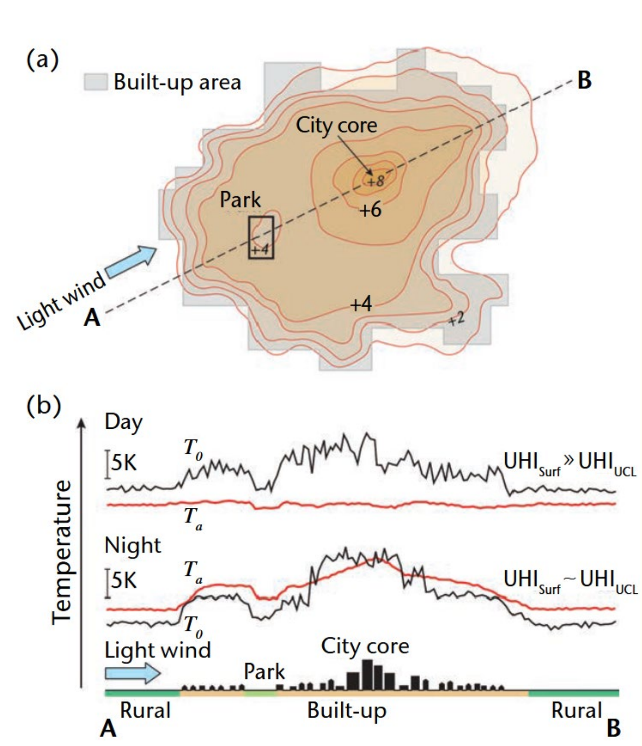
Urban Heat Island (UHI)

$$UHI = T_{urban} - T_{rural}$$

UHI types include	urban	rural
Canopy Layer	e	
Surface	d or a	

Oke et al. 2017: Fig. 2.2

UCL vs Surface



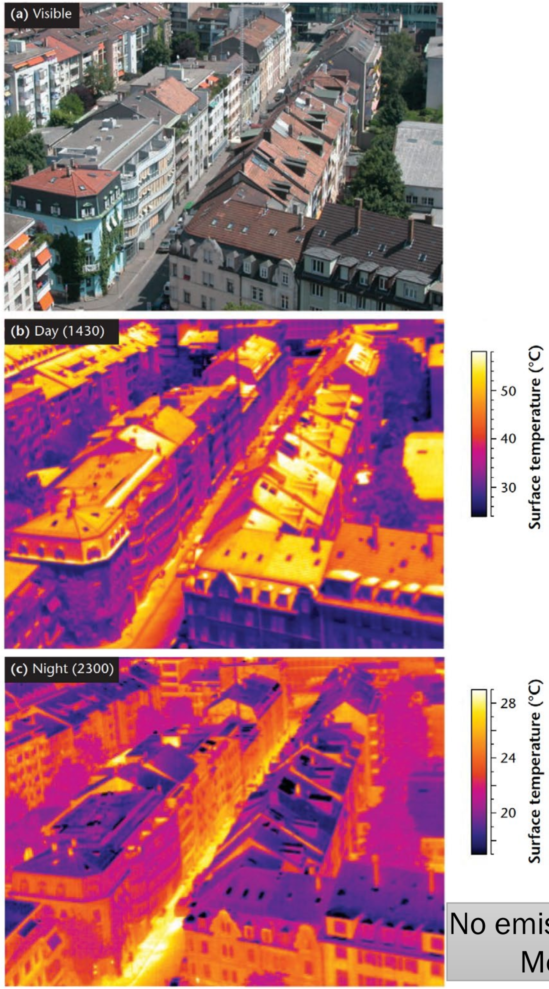
Day

Night

T_a – air

T_0 surface

WMO 2023 Fig 2.3 | Oke et al. 2017

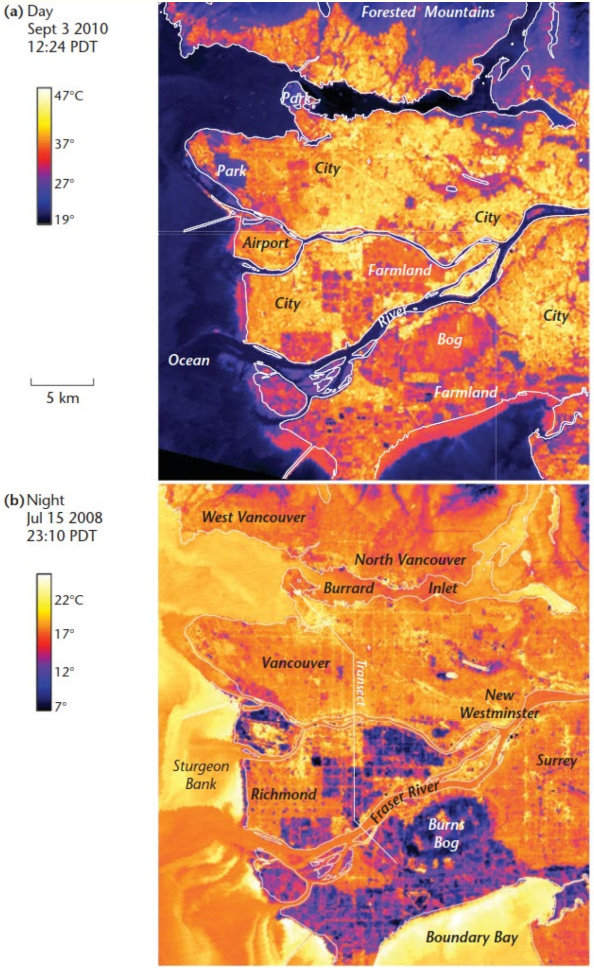


Day

Night

No emissivity correction
Metals⟶cold

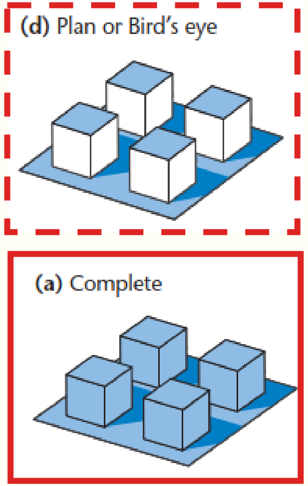
Figure 7.4 **(a)** Photograph of Sperrstrasse canyon in Basel, Switzerland and adjacent courtyards (Credit: J. Voogt), and **(b)** thermal image of same canyon at 1430 h, and **(c)** at 2300 h on July 12, 2002 (Credit: J. Voogt). Viewing direction is to the NE. No correction for surface emissivity hence metals appear anomalously 'cold' (e.g. tower, skylight flashing, metal roofs).



Day

Night

Figure 7.7 Thermal images of surface brightness temperature for Vancouver, Canada. **(a)** Daytime: September 3, 2010 at 1224 PST. **(b)** Nighttime: July 15, 2008 at 2310 PST. Observations from the ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer) instrument on the Terra satellite. Temperatures for Band 13: 10.25-10.95 μm, corrected for atmospheric but not emissivity or surface geometry effects; pixel size 90 m.



No emissivity /geometry corrections
ASTER

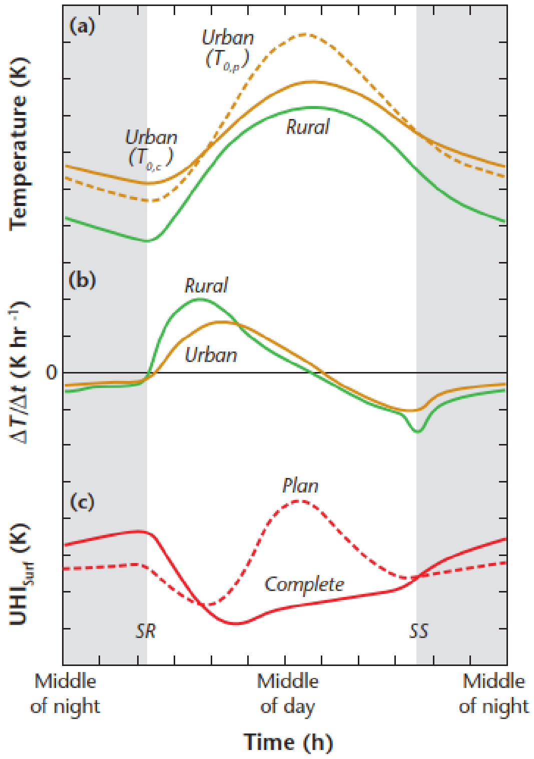


Figure 7.9 Schematic **(a)** temporal variation of urban complete, urban plan and rural surface temperature on a day with fine weather, **(b)** associated urban complete and rural warming/cooling rates, and **(c)** temporal evolution of the UHI_{Surf} for both the plan and complete surface. Vertical scale units are approximately 5 K, 1 K h^{-1} and 2 K respectively.

Oke et al. 2017

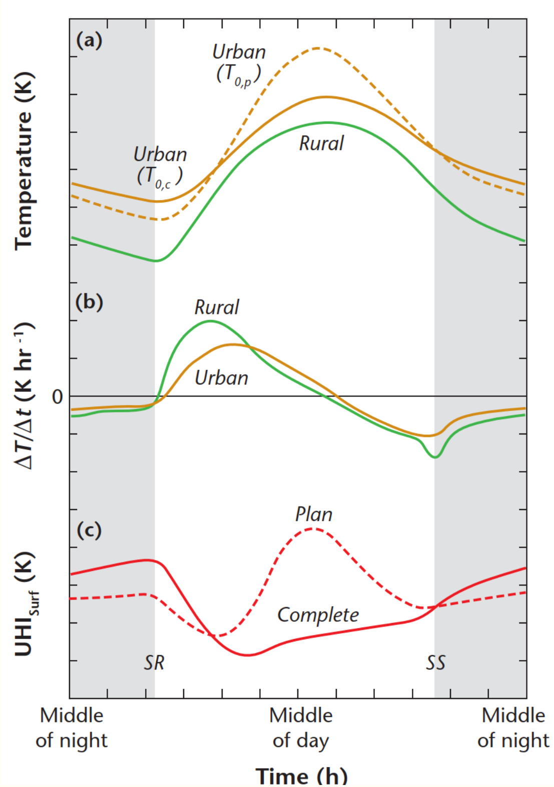


Figure 7.9 Schematic **(a)** temporal variation of urban complete, urban plan and rural surface temperature on a day with fine weather, **(b)** associated urban complete and rural warming/cooling rates, and **(c)** temporal evolution of the UHI_{Surf} for both the plan and complete surface. Vertical scale units are approximately 5 K, 1 K h^{-1} and 2 K respectively.

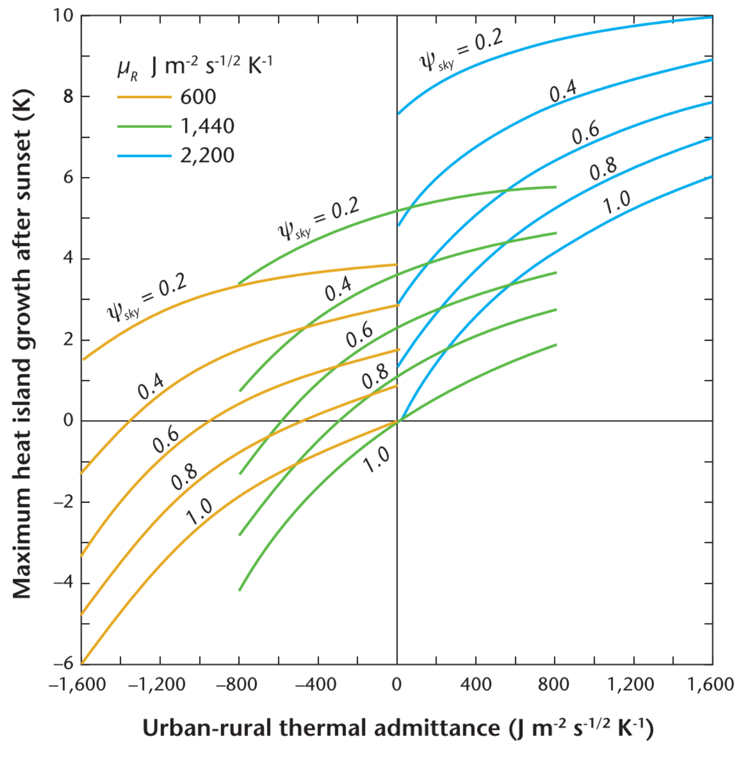
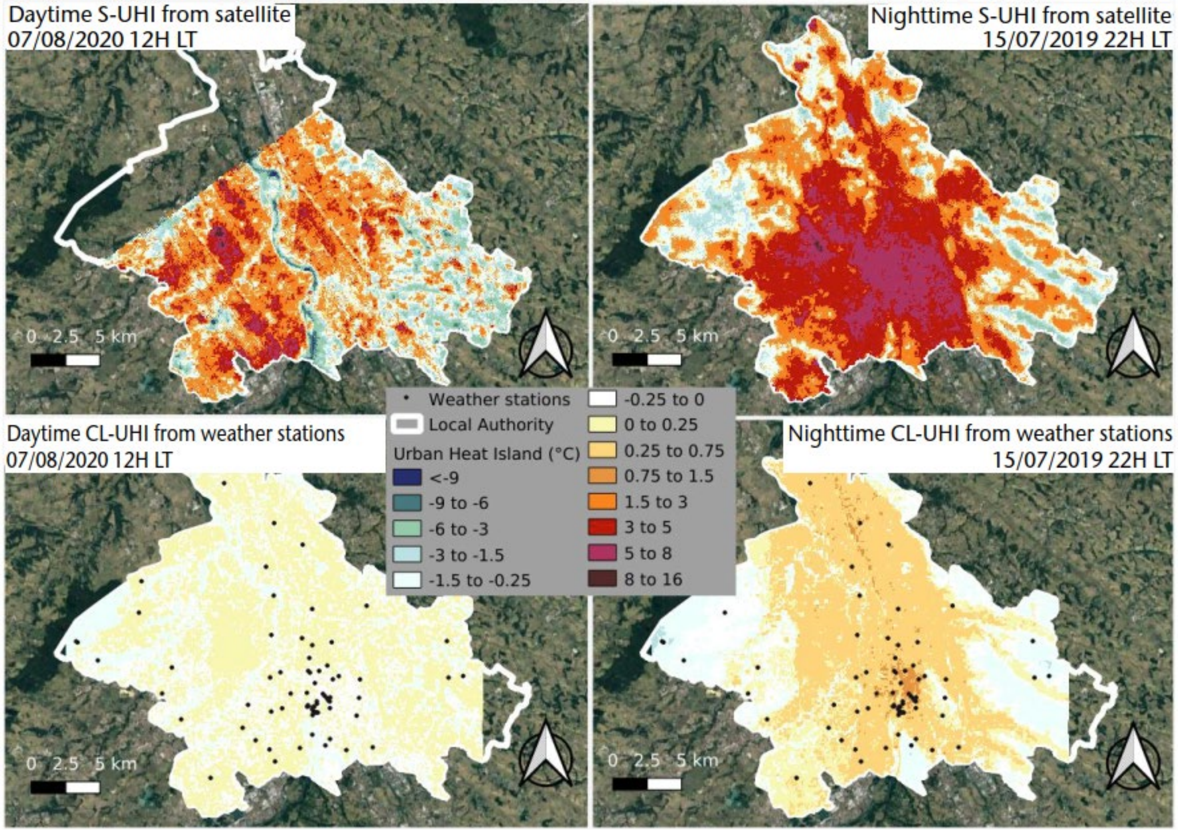


Figure 7.11 Predicted maximum magnitude of nocturnal UHI_{Surf} in 'ideal' weather using a 1-D SEB model as a function of the difference between surface thermal admittance of rural and urban environments ($\Delta\mu_{U-R}$). Variables: sky view factor of canyons in city centre (ψ_s), and absolute rural value (μ_R). Urban T_0 is represented by $T_{0,floor}$ in this analysis (Source: Oke et al., 1991; © Kluwer Academic Publishers, used with permission from Springer).

Oke et al. 2017

Day Night



Toulouse, France

S-UHI
ECOSTRESS satellite, 70 m resolution

CL-UHI
spatially interpolated
obs (dots) to 250 m using
urban fraction and altitude

WMO 2023 Fig A3.1 (Touati et al., 2020)

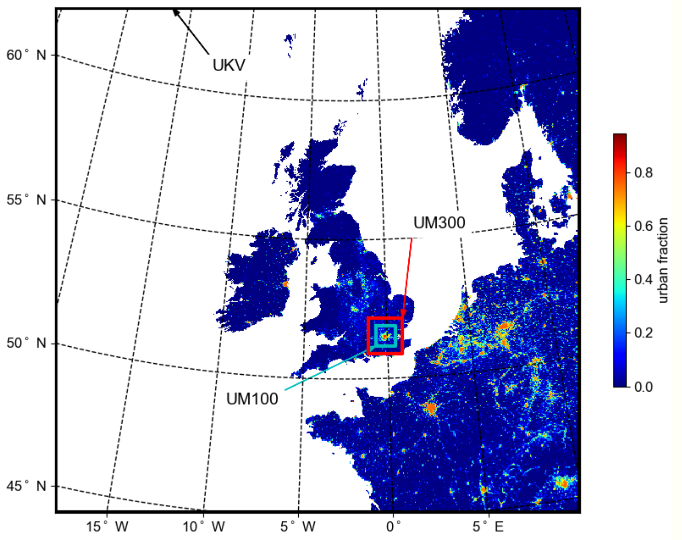
Applications

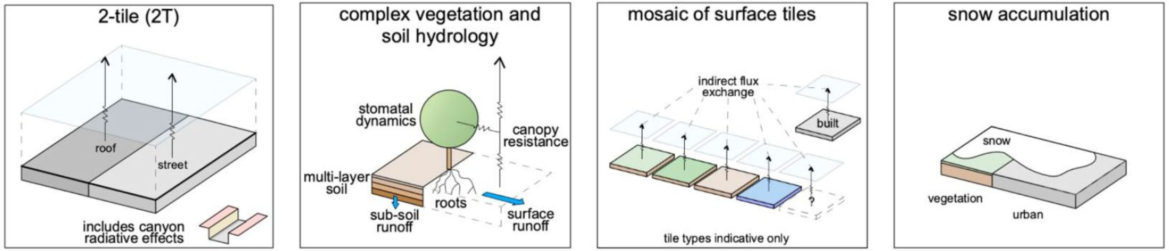
- Urban Heat Island
- NWP – numerical weather prediction
    - Hall et al. evaluating LST @ 100 m NWP/Climate
- Urban canopy Modelling
    - Stretton evaluation of Radiation Modelling for NWP/Climate
- Building Energy modelling
    - Xie – impact on building energy use
- Complementing other field observations
    - urbisphere

Next generation high resolution NWP

Model	Horizontal grid length	# grid points	Vertical levels	Time step	Lateral-boundary updated	
Global	17 km	1536 x 1152	70	12 min	n/a	Global, Atmosphere and Land (GAL 6.1) Walters et al (2017)
UKV	1.5 km	950 x 1025	70	1 min	60 min	Tang *et al.* (2021) Regional, Atmosphere and Land 3 (RAL3)
UM300	300 m	430 x 430	140	12 s	15 min	Boutle *et al.*(2016) RAL3
UM100	100 m	800 x 800	140	3 s	15 min	Lean et al. (2019) RAL3

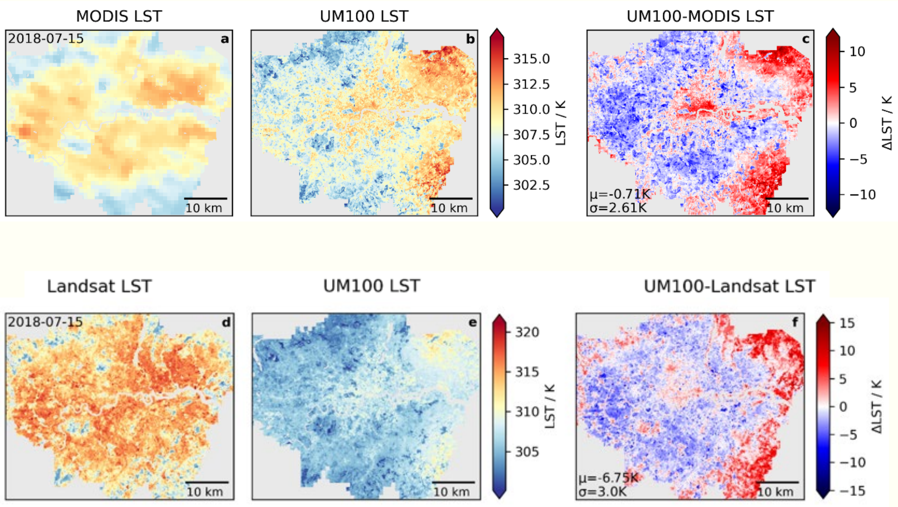
- Met Office's non-hydrostatic Unified Model (UM) v12.0
  - research configuration
- UM100 domain: 80 km x 80 km
  - covering Greater London
- Land surface: JULES
  - 10 tiles different properties (e.g. emissivity)
  - MORUSES

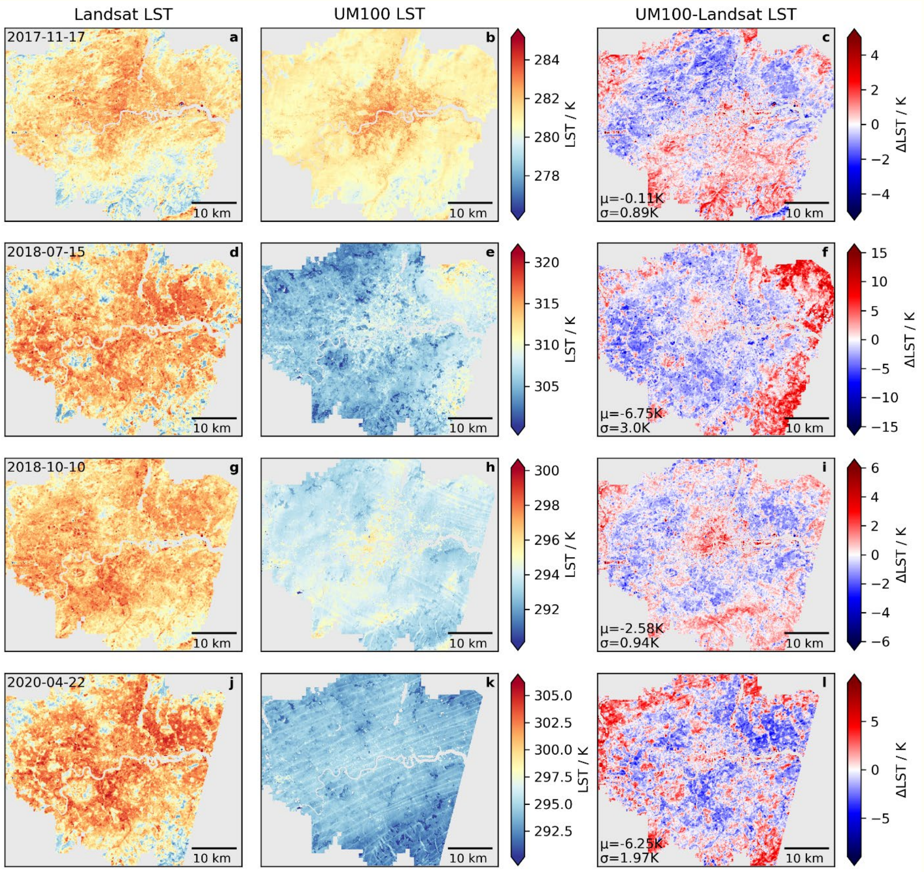




Lipson et al. 2024 QJRMS | Hall et al. 2024 QJRMS

Evaluation of UM100 with satellite thermal IRT

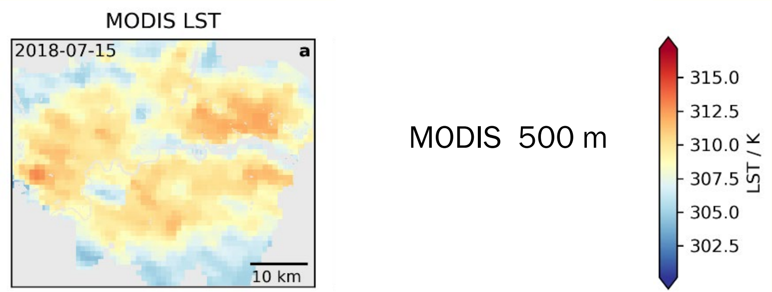




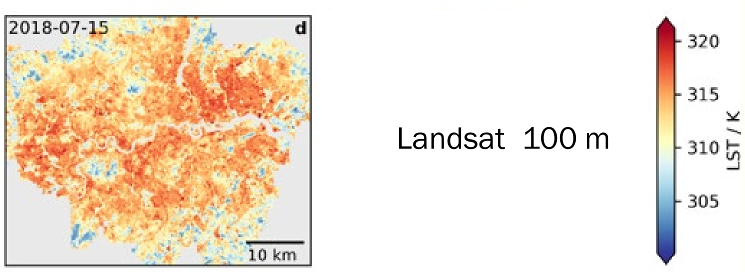
- Many high resolution (100 m) model runs done
- Improved a wide range of issues associated with downscaling
    - e.g. soil moisture, leaf area index
- ‘Final’ version – other issues apparent
- View angle effects (Morrison et al. 2023)– have an impact

Hall et al. 2024 QJRMS

Satellite and Surface LST

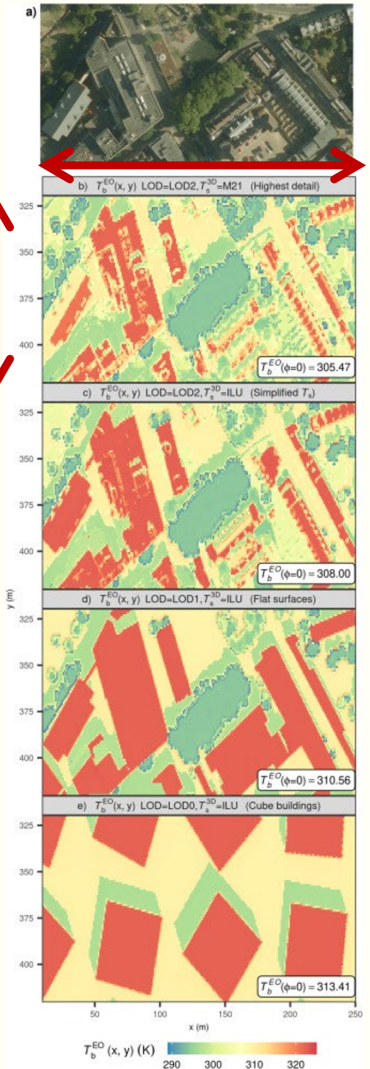


MODIS 500 m



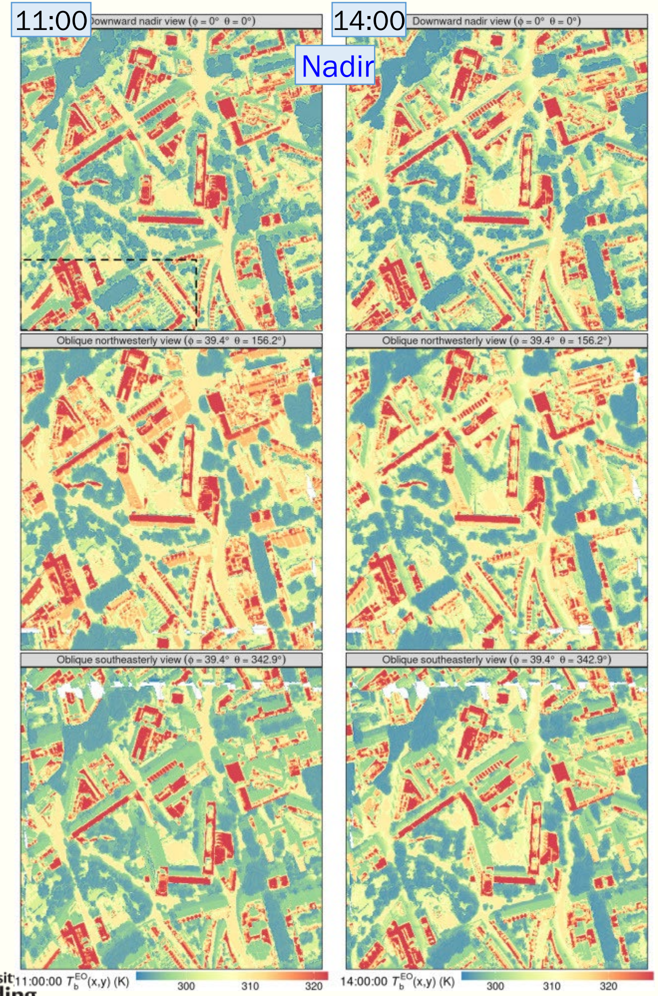
Landsat 100 m

250 x 100 m



Hall et al. 2024 QJRMS | Morrison et al. 2023 RSE

Surface-leaving radiance simulated brightness temperature

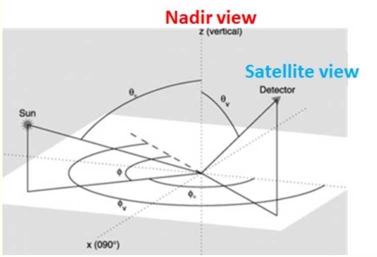


Satellite view simulations using:

- 3D DART radiative transfer model
- Ground-based surface temperature observations

- View angle varies with: satellite and time
- Changes view of roof - ground – walls (& their orienta

Off –nadir
Zenith angle



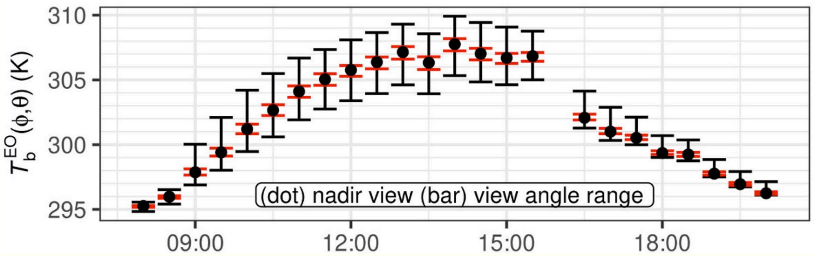
27th August 2017

- Met Office MORUSES assumes planar vertical and horizontal surfaces
- θ = 0° north θ = 90° east
- ϕ = 0° up from surface ϕ = 90° parallel to surface

Morrison et al. 2023 RSE

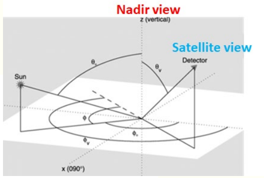
Satellite view simulations

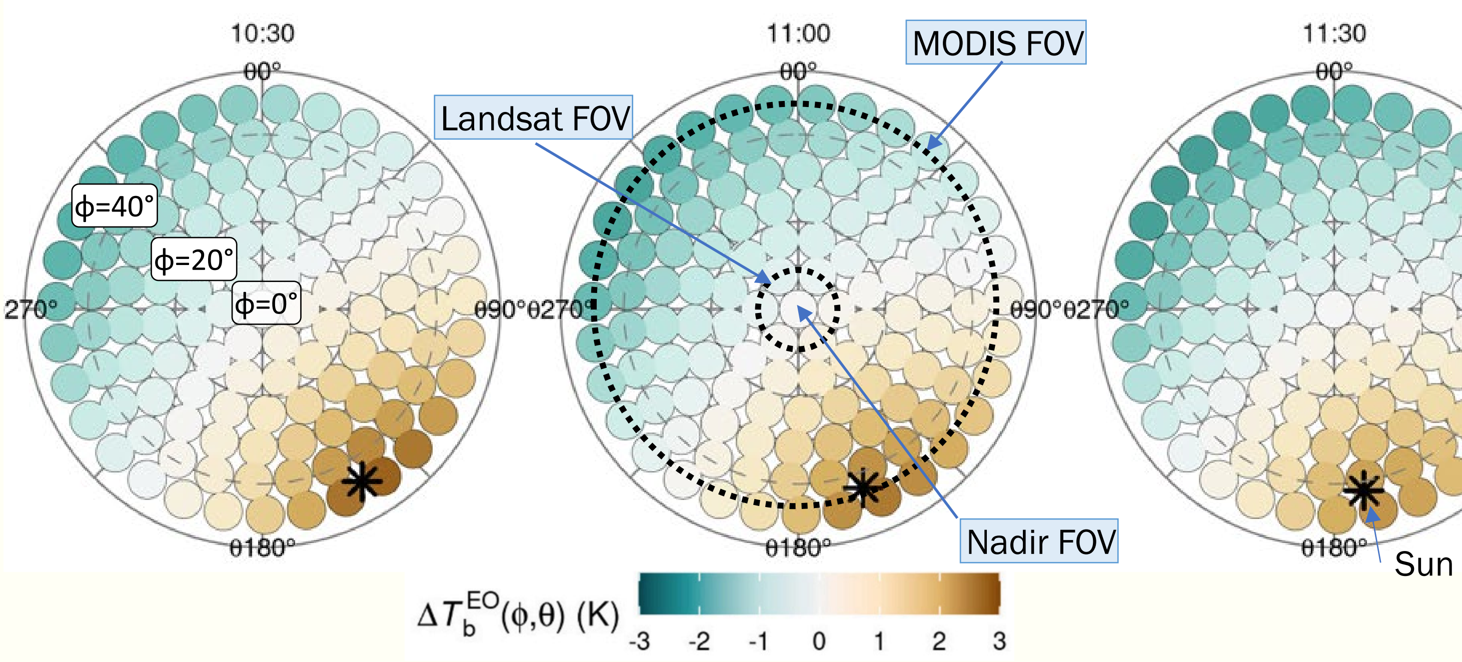
- Difference between nadir and angle (actual) view
- MODIS: up to ±45° view angle (typical of multi-day observations)
  - ~4.5 K view-angle variation
- Landsat: ±7.5° view angle
  - ~0.7 K view-angle variation



$$\Delta T_b^{EO} = T_b^{EO}(\phi = 0) - T_b^{EO}(\phi, \theta)$$

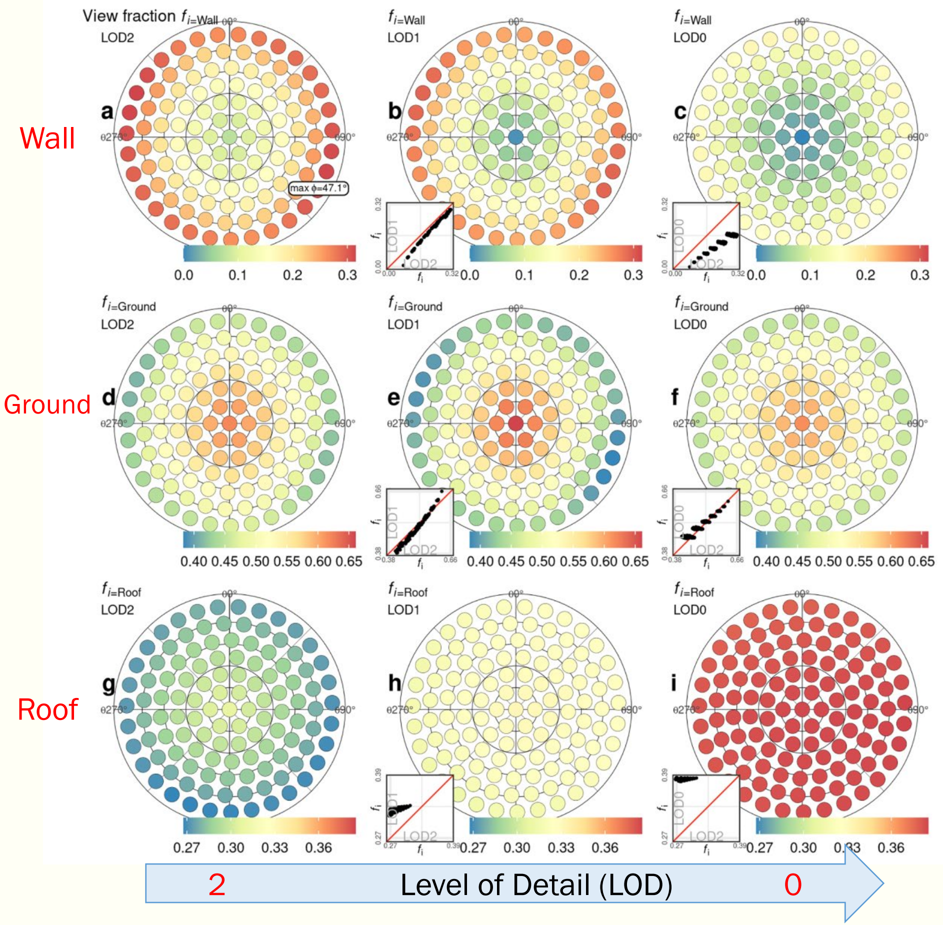
Nadir View Satellite view

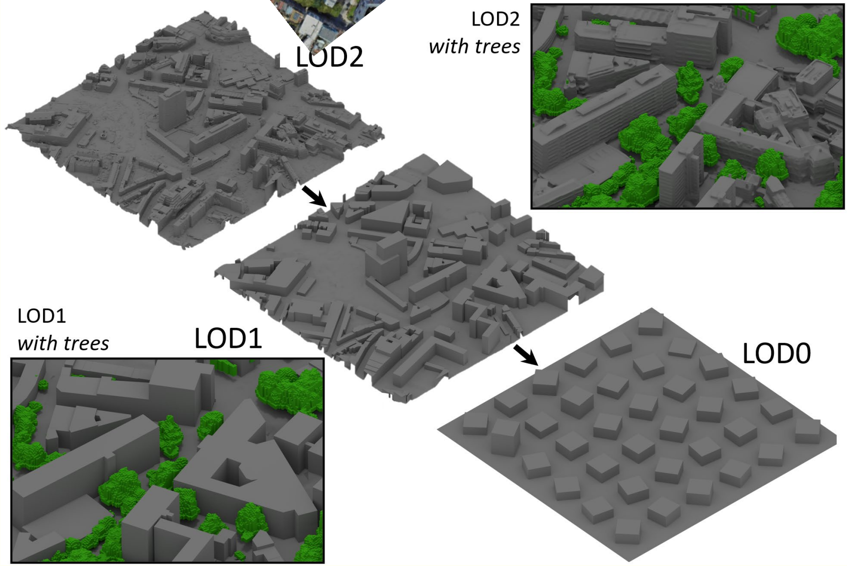




Morrison et al. 2023 RSE

Views of surface seen by satellite





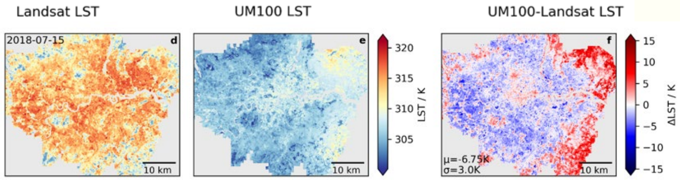
Morrison et al. 2023 RSE

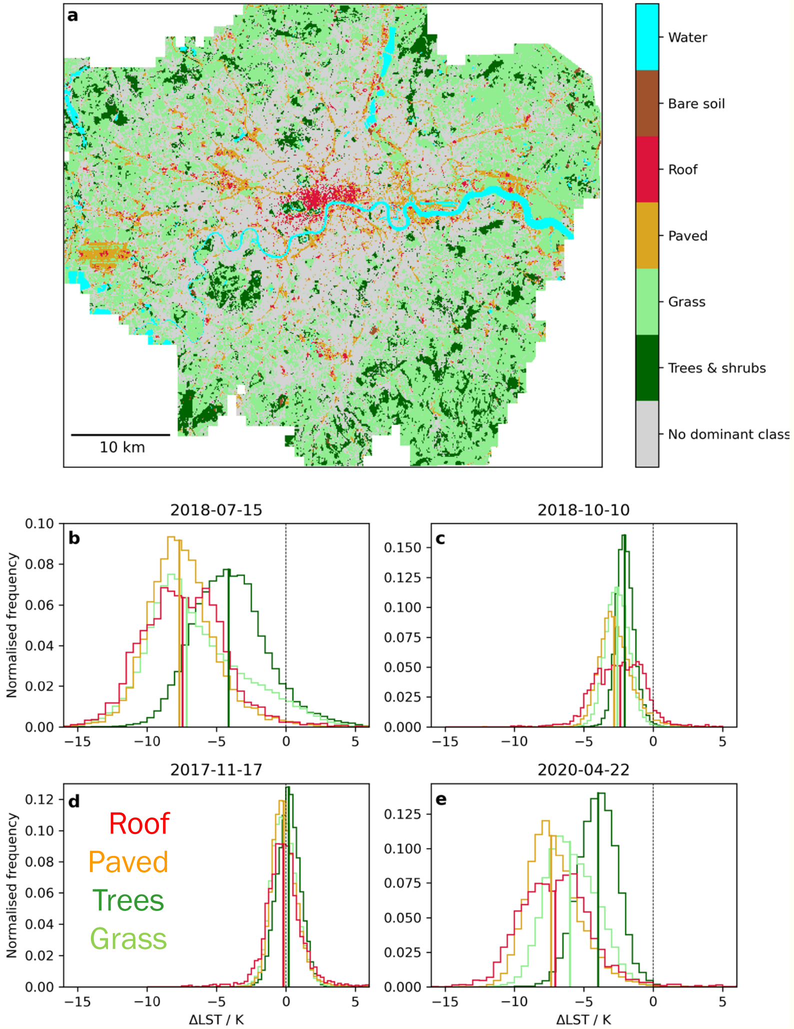
UM100 – Landsat LST differences

- Grids> 50% a particular surface type

- Model performance varies with land cover
- Poorer for more built-up areas

- Next steps
    - To evaluate more fully



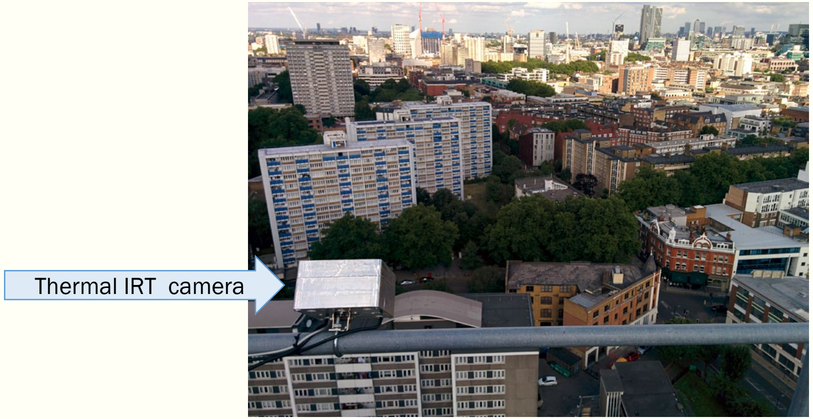


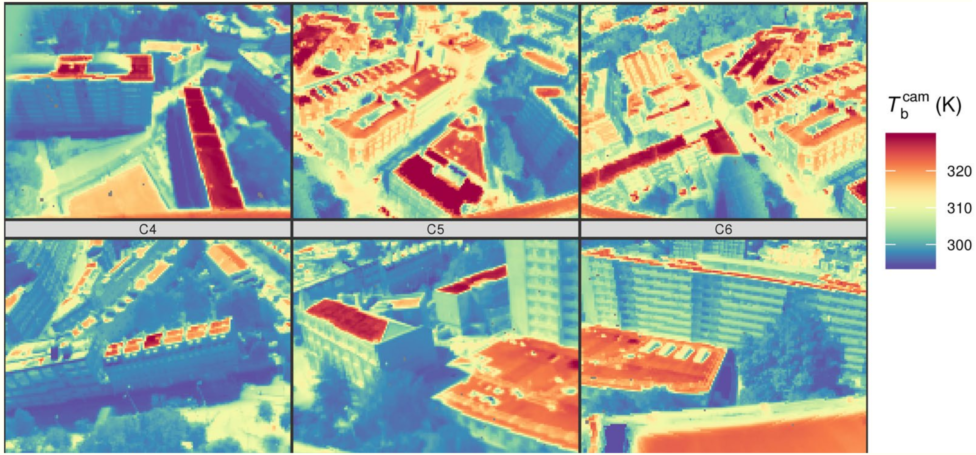
Hall et al. 2024 QJRMS

Applications

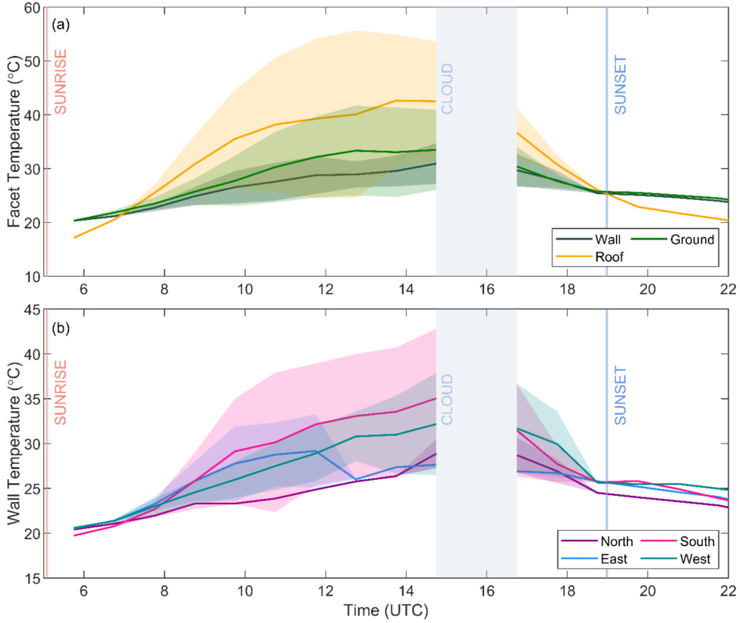
- Urban Heat Island
- NWP – numerical weather prediction
    - Hall et al. evaluating LST @ 100 m NWP/Climate
- Urban canopy Modelling
    - Stretton - evaluation of Radiation Modelling for NWP/Climate
- Building Energy modelling
    - Xie – impact on building energy use
- Complementing other field observations
    - urbisphere

Surface Temperature: London





27 August 2017



Sunlit – shaded mean

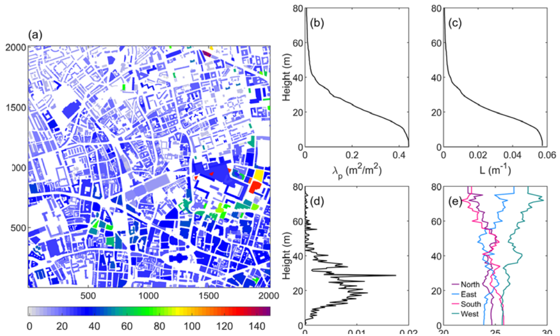
Morrison *et al. 2020 RSE* | Stretton et al. 2023 GMD

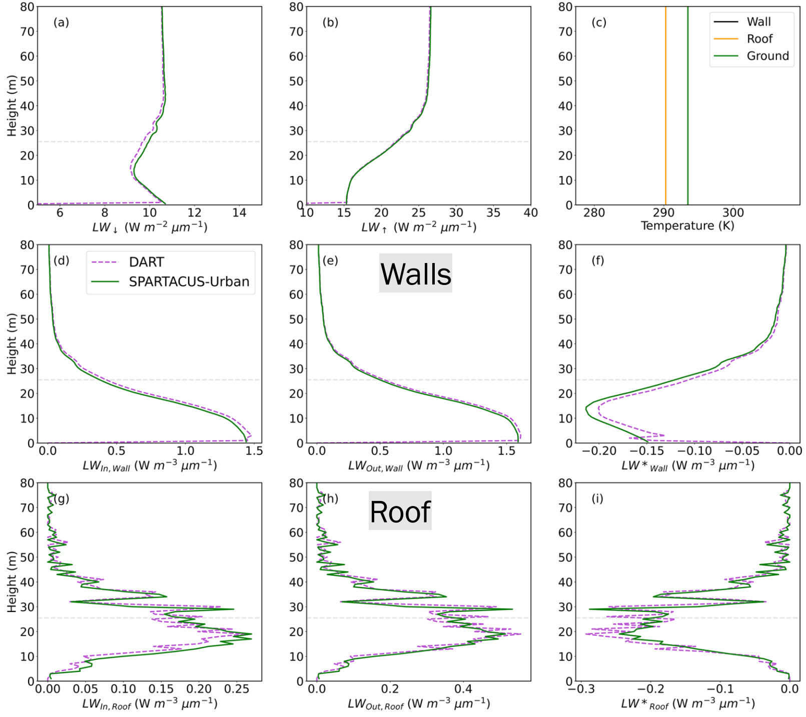
Evaluation of NWP radiation models with vertical variations

central London

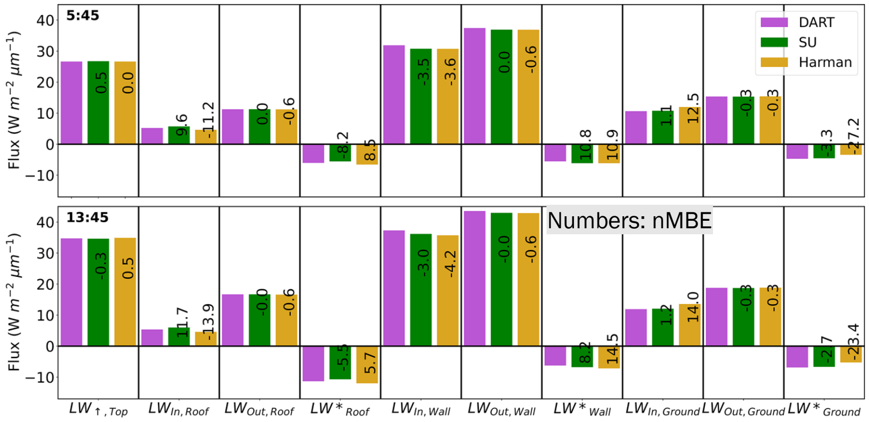
- DART (3D model) (Gastellu-Etchegorry)
- SPARTAUCUS-Surface (Hogan)
- JULES/MORUSES (Harman)

2 km x 2 km grid resolution





Constant surface temperature per facet, varying in time

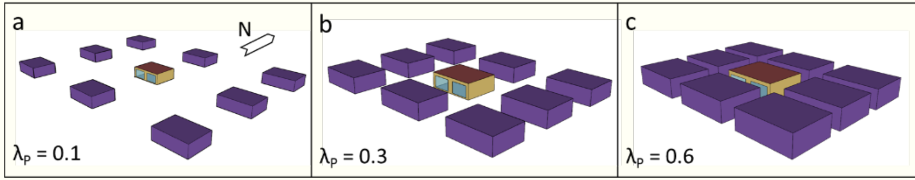


Model	n	N	Time (s)	Time relative to Harman
Harman	1	–	2×10^{-5}	–
SPARTACUS-Urban	1	8	3×10^{-5}	1.5
	6	8	4×10^{-4}	20
	151	1	2×10^{-3}	100
	151	4	2×10^{-3}	100
	151	8	2×10^{-3}	100
DART	151	–	6.6×10^{4}	3.3×10^{9}

Stretton et al. 2023 GMD

urbisphere
University of Reading

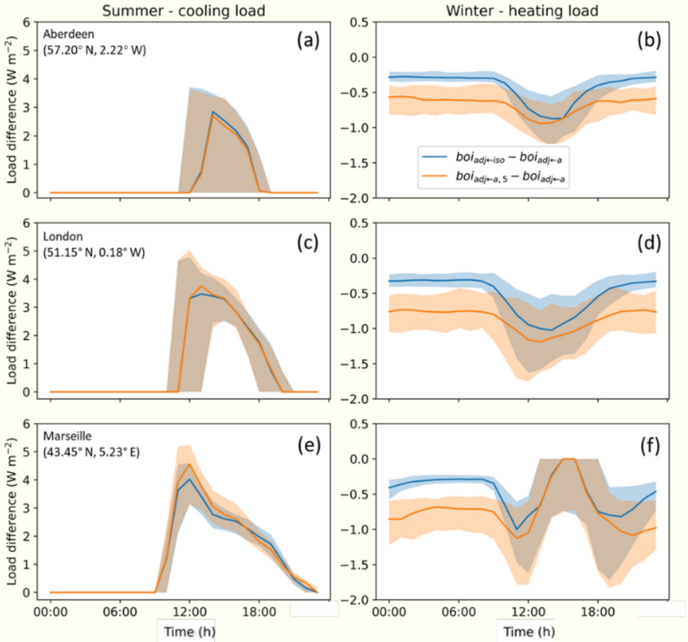
Longwave radiative exchanges: inter-building



Building design
- default EnergyPlus method large bias in all metrics
- Larger impact:
  - **denser neighbourhoods** (λ_P = 0.3, 0.6)
  - lower latitudes

Default method bias:
- external wall temperature:
  - midday median: 3 °C *underpredicted*
- annual energy demand:
  - Cooling: 17.1% underpredicted
  - Heating: 6.2% overpredicted
- annual overheating degree hours
  - day (> 28 °C): 24.5% underpredicted
  - night (> 26 °C): 60.1% underpredicted

Observations: Infra-red thermal camera
Model: EnergyPlus
- new iterative method to determine LW radiation exchange on external building envelope
- SUEWS/RSL



Xie et al. 2022: *Building and Environment*

Final Comments

- Many challenges in the urban environment
  - Scale of the urban form
  - Viewing the facets of the urban
  - Variability of the urban form
  - Urban materials
  - Urban activities
  - Complexity – these are combined and dynamic

- Provide Research opportunities
- Need to consider – think about implications of assumptions

- Applications in the urban environment
  - Urban Heat Island
  - Building Energy Modelling
  - Weather (NWP)/ Climate
  - Urban Canopy Modelling

- 100s+ applications
- Many important implications: environmental, health, economic, social, justice, planning....
- Decisions – in cities and their implementation are made at the micro-scale – but scale to country to regional impacts
- Finding problems, assessing the remediation .....

References

Author (et al.)	YYYY	https://doi.org/
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Hall	2024	10.1002/qj.4669
Hang	2022	10.1016/j.buildenv.2022.109618
Hertwig	2024	GD - minor revisions
Kotthaus	2014	10.1016/j.isprsjprs.2014.05.005
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Lipson	2024	10.1002/qj.4589
Liu	2022	10.5194/acp-22-4721-2022
Liu	2024	10.1016/j.enbuild.2024.114668
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Morrison	2020	10.1016/j.rse.2019.111524
Morrsion	2021	10.1016/j.uclim.2020.100748
Morrison	2023	10.1016/j.rse.2019.111524
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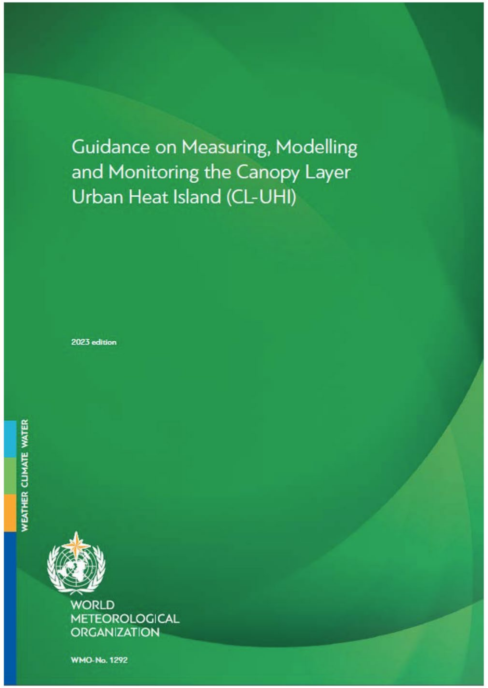
Wu	2024	10.1016/j.rse.2024.114003
Xie	2022	10.1016/j.buildenv.2021.108628

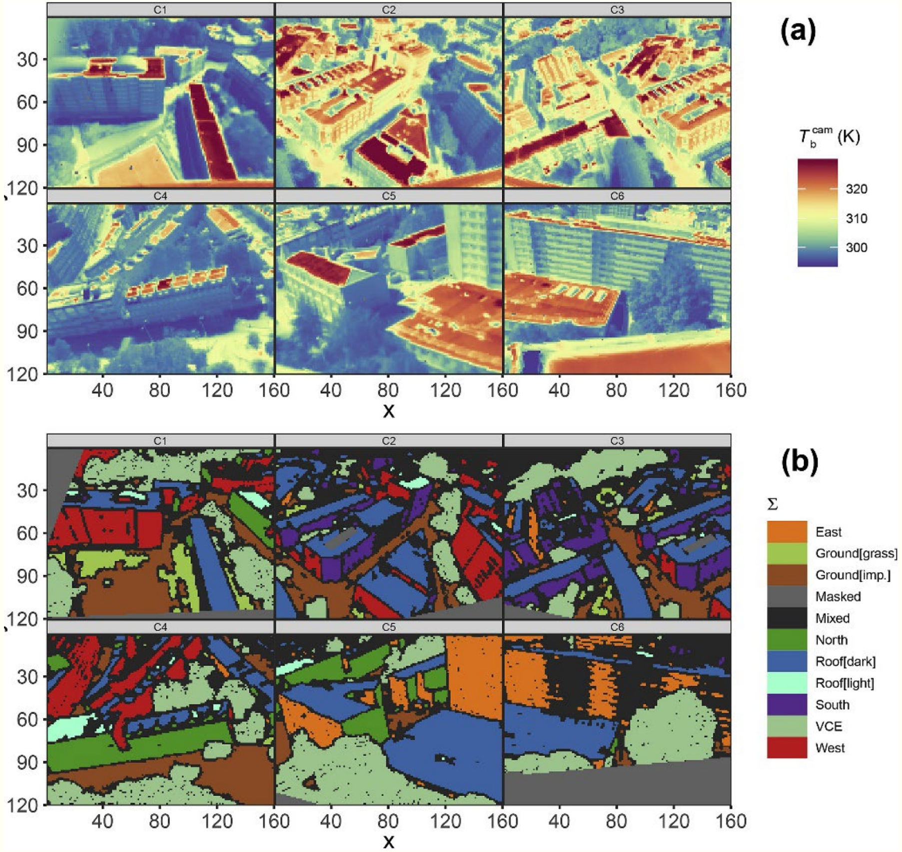


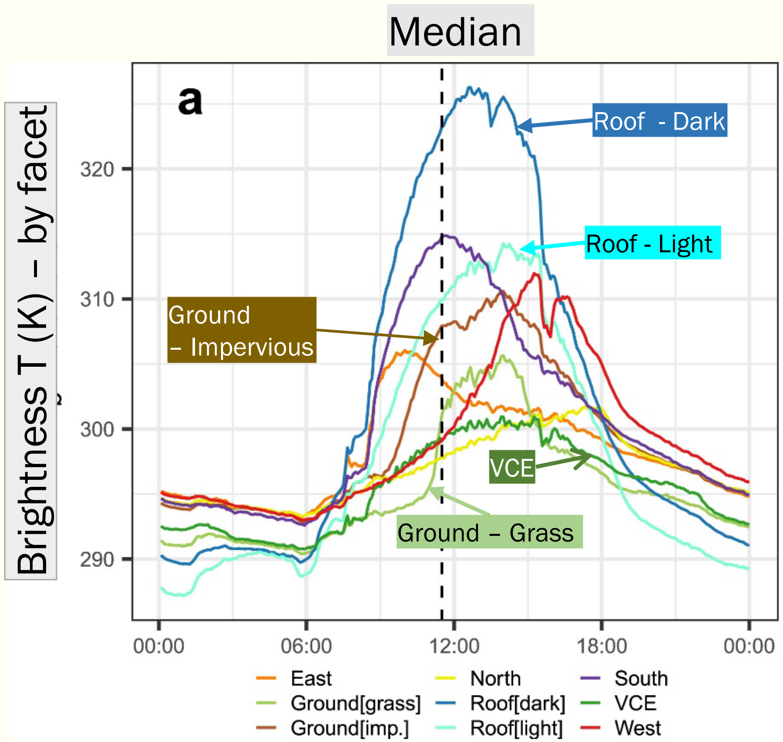
Spatial scales – things to consider

- Satellite – pixel resolution
  - Time/space constraints

- Urban Form resolution
  - dimensions
  - Building
  - Streets
  - Vegetation

Geometry and Materials





VCE - Vegetation

Morrison et al. 2020 RSE

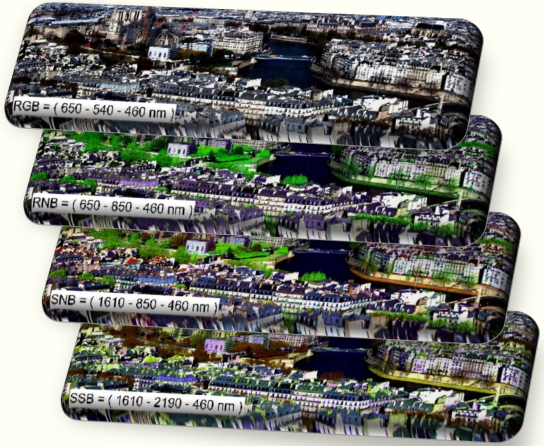
Multi-scale identification and mapping of urban surface radiative properties

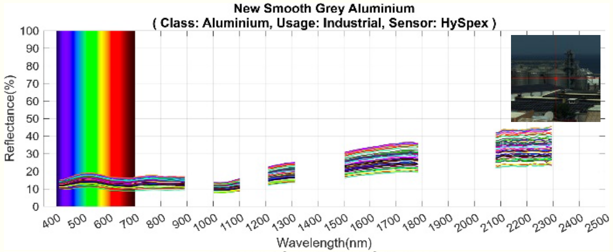
HySpex VS-620 Camera

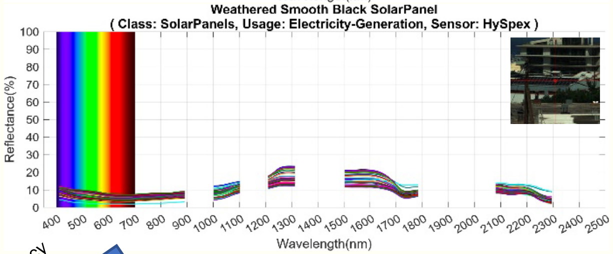
Vertical Measurements

Horizontal Measurements

Hyperspectral Imaging





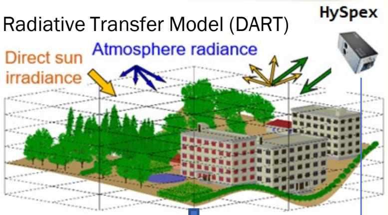


Hyperspectral Library

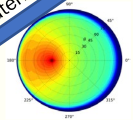
Satellite Image

Radiative properties at city / regional scale (e.g. albedo)

3D Radiative Transfer Model (DART)



Angular Dependency per material class



3D Model

\+

X-SVM Model

3D Material Classification

Convolutional NN from DART to HySpex

Extrapolation

WorldView-3 (2 m)

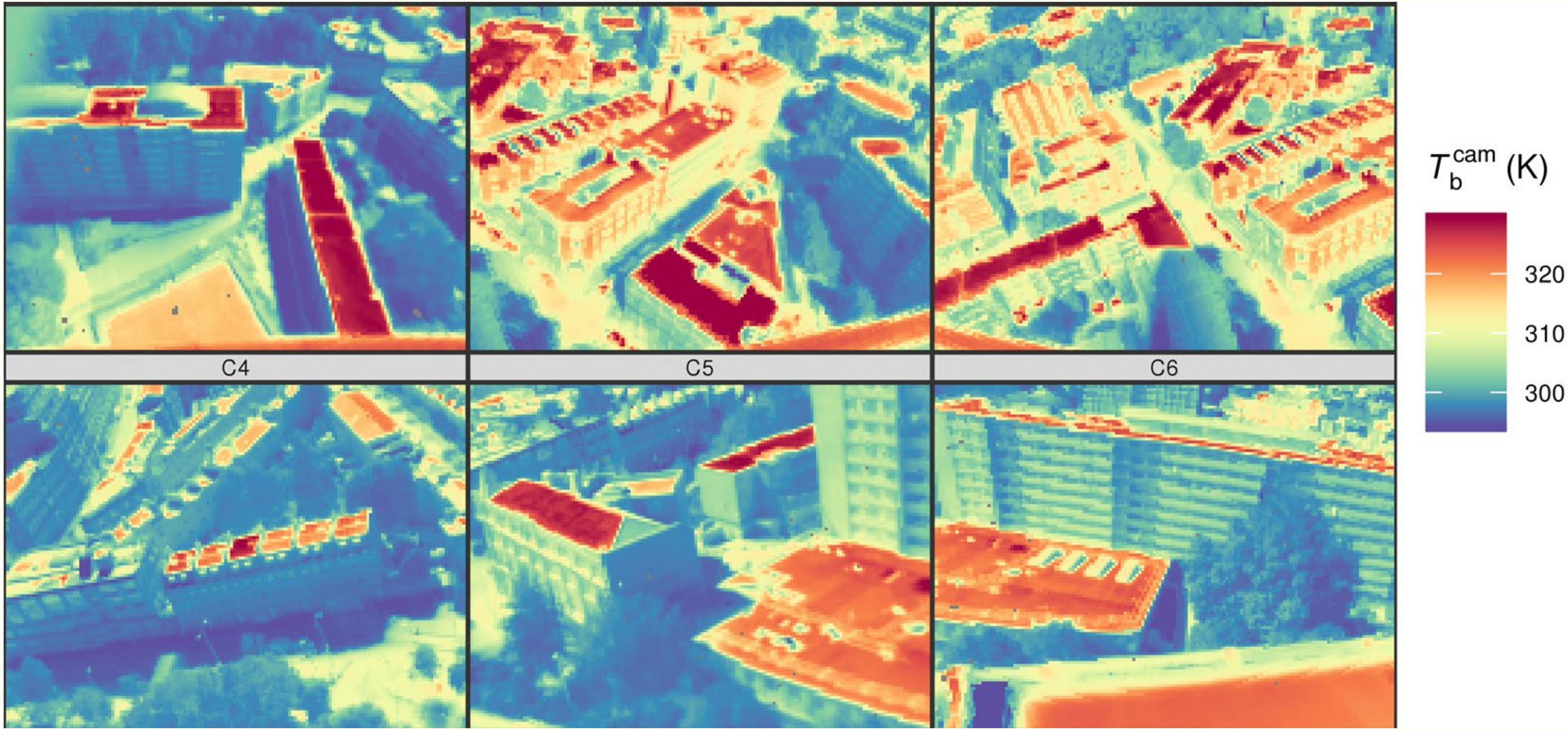
Sentinel-2 (10 m)

EnMap (30m)

Lantzanakis et al. 2024 urbisphere PhD - FORTH/Freiburg

urbisphere

University of Reading

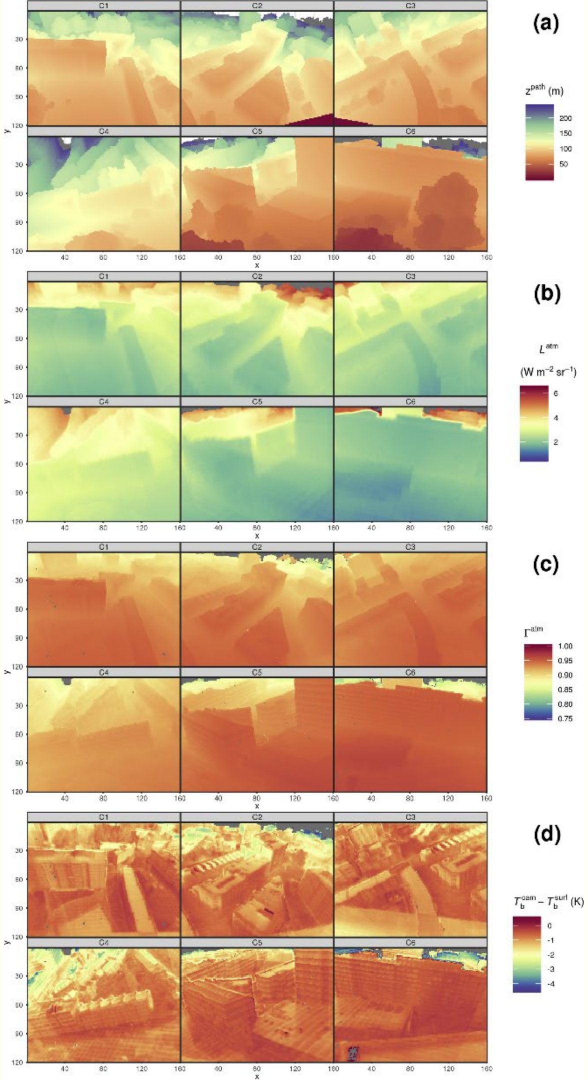


Morrison et al. 2020 RSE

Atmospheric correction variables

- per camera
- at 12:00
- 24 Sep. 2017

Morrison et al. 2020 RSE



Surface – sensor path length (z^{path}, m)

Band integrated longwave emission from the atmosphere

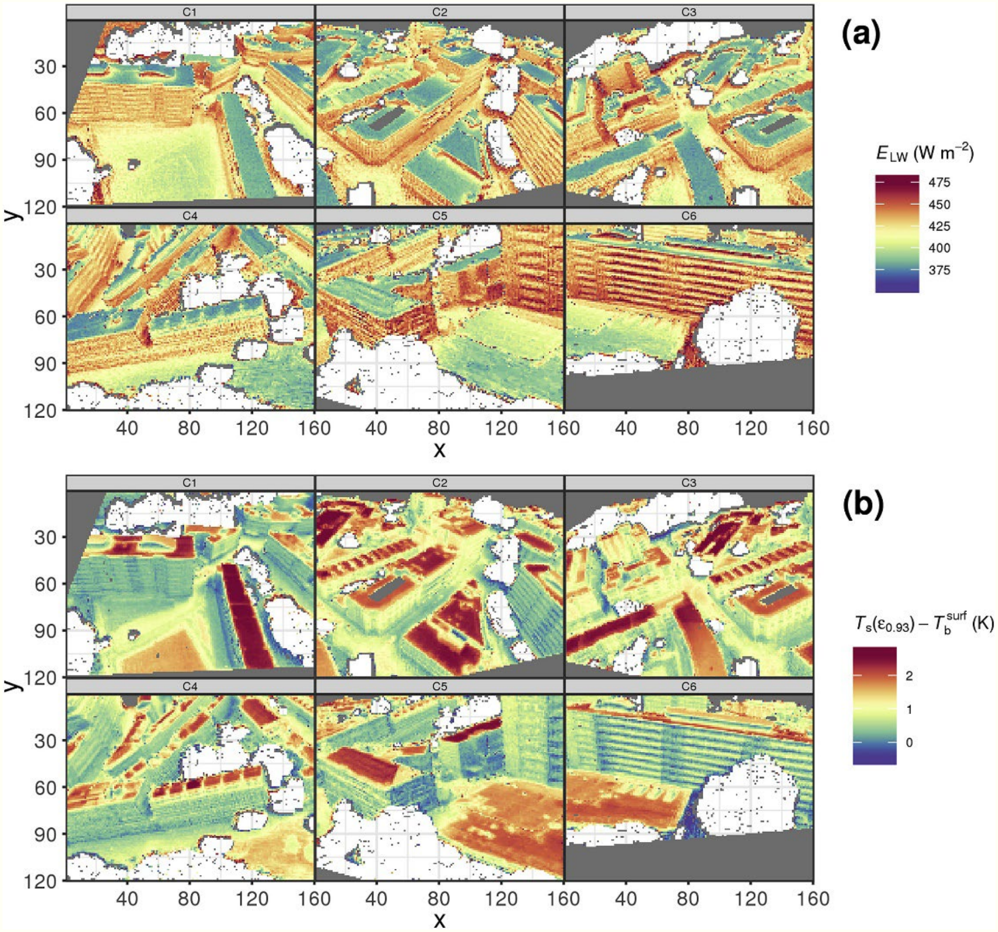
$[L^{atm}(x, y) = \int_{7\mu m}^{14\mu m} d\lambda \cdot R_\lambda(x, y) \cdot L_\lambda^{atm}(x, y)]$ with $d\lambda = 0.2$ and $R\lambda(x, y)$ the sensor spectral response function

Band integrated atmospheric transmissivity

$[\Gamma^{atm}(x, y) = [L^{cam}(x, y) - L^{atm}(x, y)] / L^{surf}(x, y)$ with L^{cam} (L^{surf}) the at-sensor (surface leaving) band radiance.

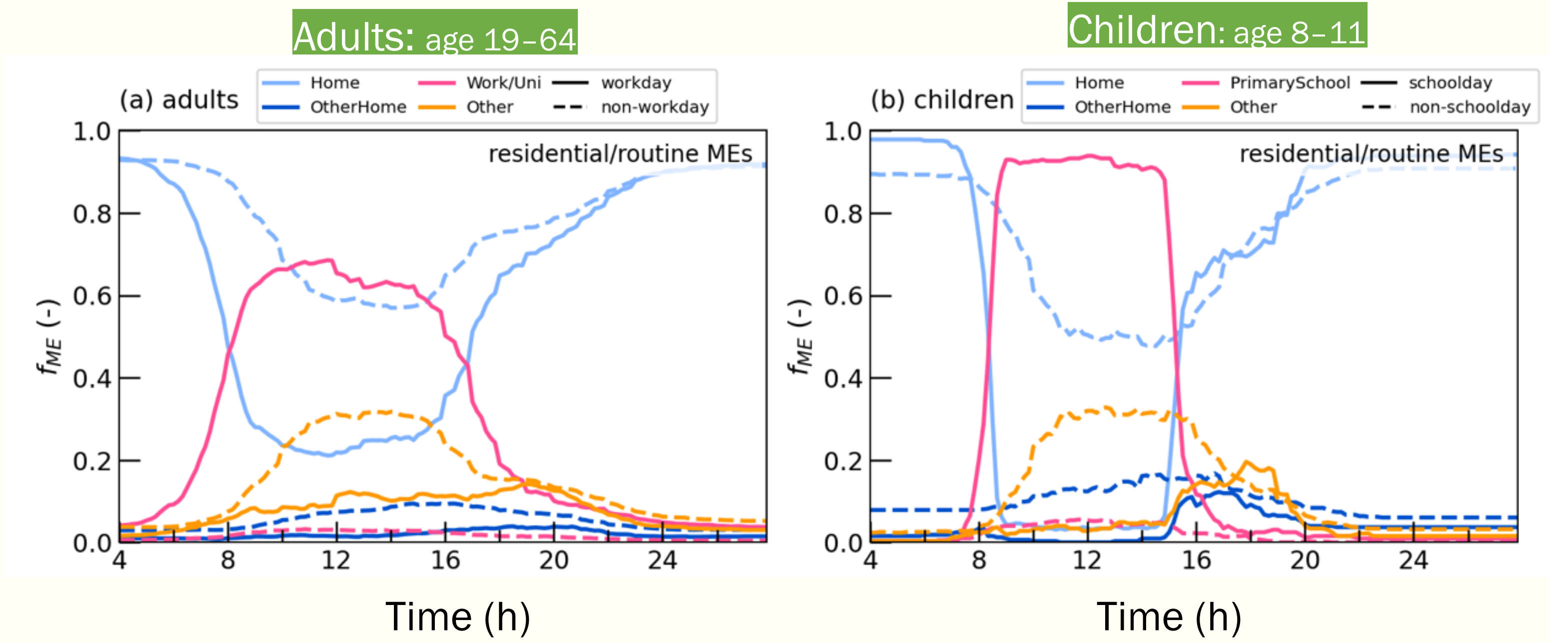
Final difference

uncorrected (T_b^{cam}) - corrected (T_b^{surf}) brightness temperature observations



Morrison et al. 2020 RSE

People spend their time in different locations: varies with age, day type, time of day



Day type

Workday

Non workday

Behaviour: SHAPE

- population
- activity profiles
- energy expenditure

people

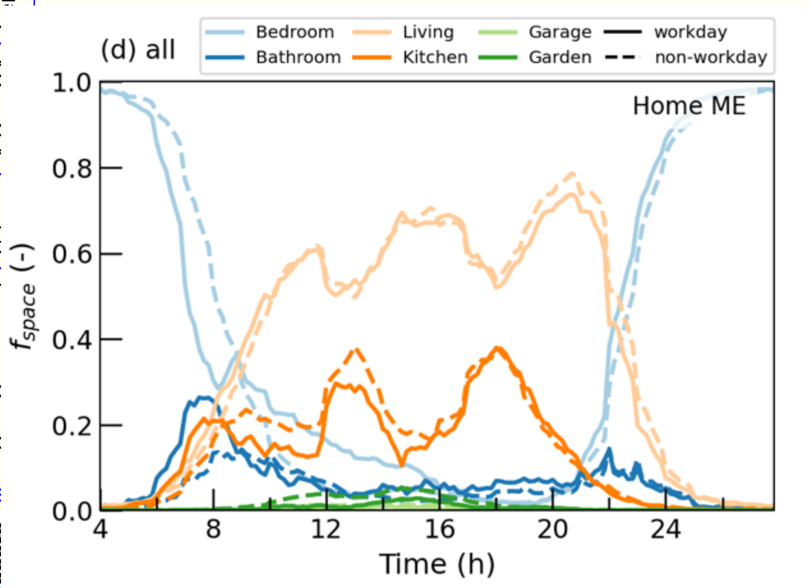
Hertwig et al. 2024: *in review*

MAPSECC: London

MAPSECC: London

- Activities in different Microenvironments

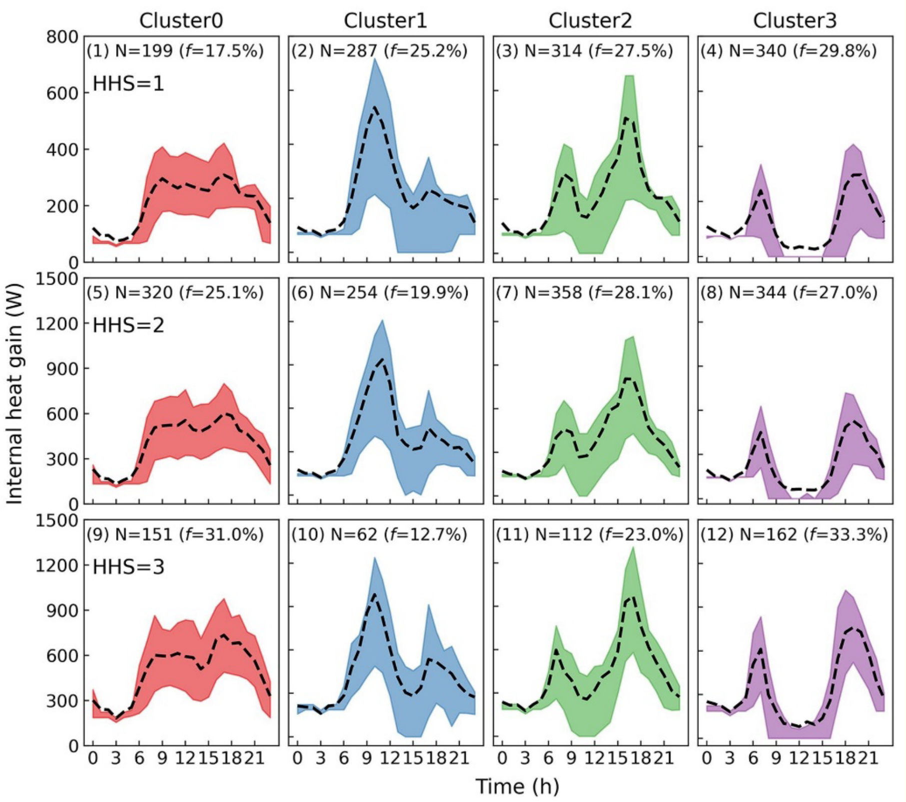
Home ME



Hertwig et al. 2024: *in review*

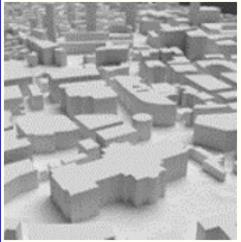
Home

Most of day | Morning | Afternoon | Early - late



Liu *et al.* 2024 [Energy and Buildings](https://doi.org/10.1016/j.enbuild.2024.114668) https://doi.org/10.1016/j.enbuild.2024.114668

Longwave evaluation of SPARTACUS-Urban using DART

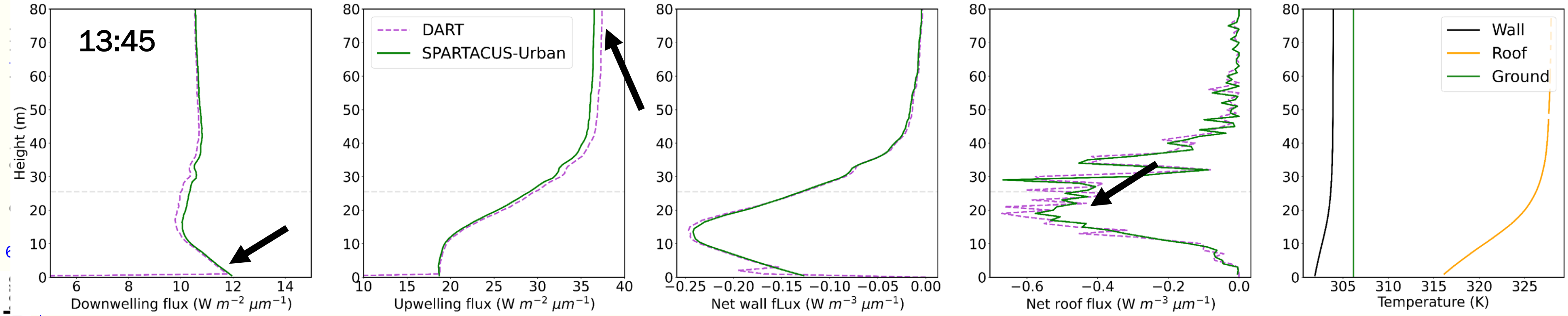


Real world – London

- Similar for single temperature and vertical profile simulations

Simulations with sunlit/shaded temperature variation:

- All nBE < 11%
- Clear air fluxes nBE < 3%
- SPARTACUS
  - Overestimates net **wall** flux
  - Underestimates net **roof** flux



Stretton et al. (2023) https://doi.org/10.5194/egusphere-2022-1002

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