First Annual Anthony J. Brazel Urban Climate Lecture

Urban meteorology & climate research: importance for integrated city services

Sue Grimmond

Meteorology, University of Reading, c.s.grimmond@reading.ac.uk

Reading: Simone Kotthaus (Paris), Elliott Warren, Christoph Kent, Will Morrison, Ben Crawford (MIT), Helen Ward (Innsbruck), Ting Sun, Denise Hertwig, Andy Gabey (IEA), Janet Barlow, Hannah Gough

Met Office@Reading: Cristina Charlton-Perez, H Lean, S Bohnenstengel, S Ballard

WMO IUWECS 2018 Guide Writing Team + A Baklanov, V Bouchet, L Molina, H Schlünzen, Jianguo Tan

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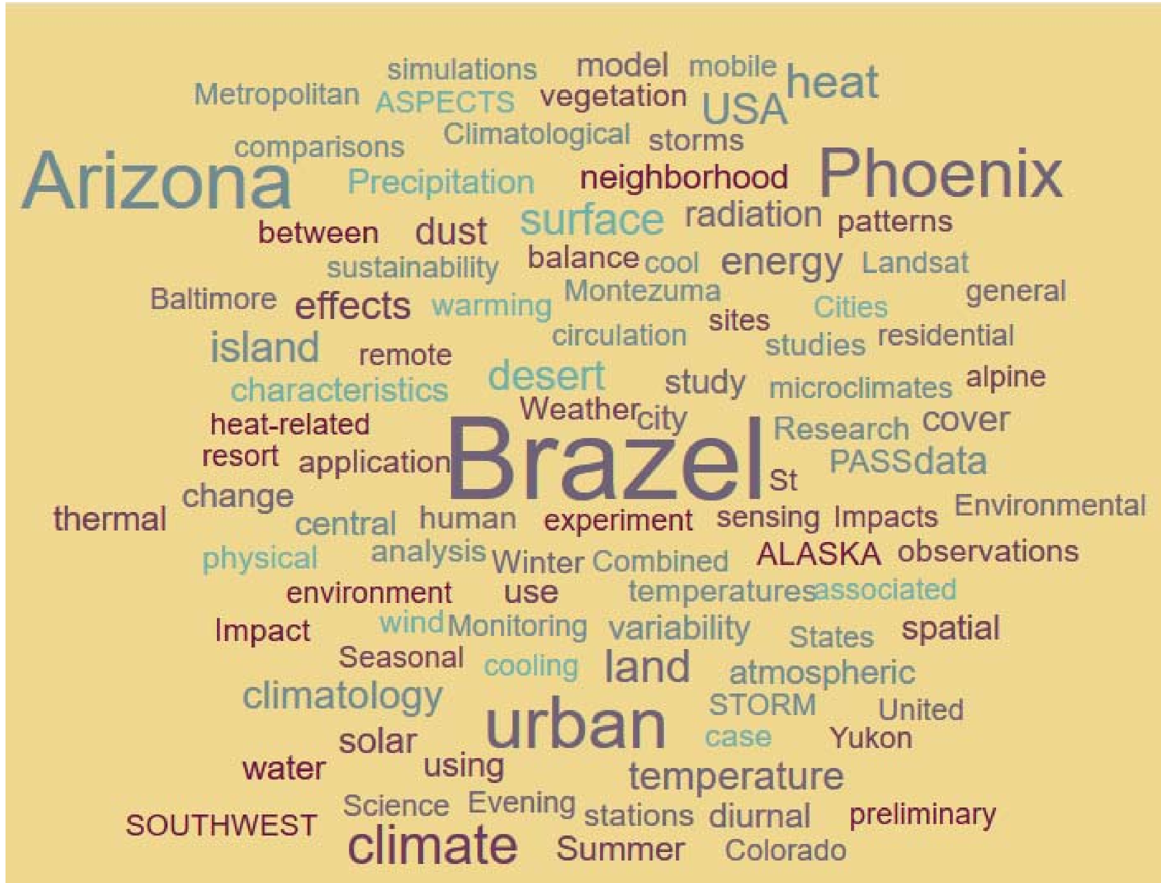


https://worditout.com/word-cloud/2762828

Data Google Citations: 2 Feb 2018, 182 Publications (Co-author names removed)

High Impact Weather

- **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)

http://i.amz.mshcdn.com/kJqIXX2gbqFhSY2-NIULy8zrSZQ=/fit-in/1440x1000/http%3A%2F%2Fmashable.com%2Fwp-content%2Fgallery%2Fheat-wave%2F0013.jpg

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.bbc.co.uk/news/uk-england-35909651 www.wmo.int/pages/prog/arep/wwrp/new/documents/Workshop_HIWeather_introduction.pdf

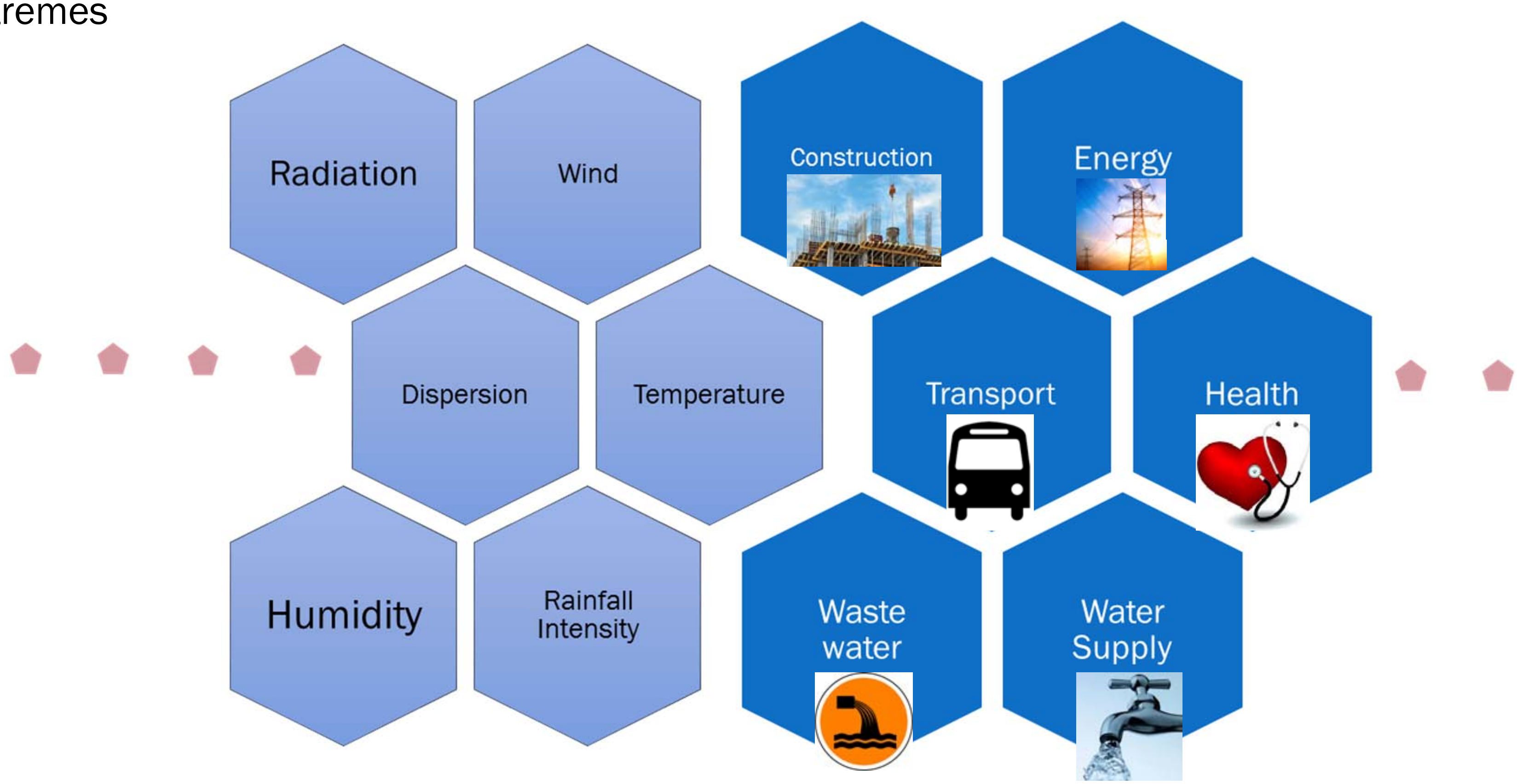
WMO for UN New Urban Agenda

Executive Council #69
- Urban cross cutting focus

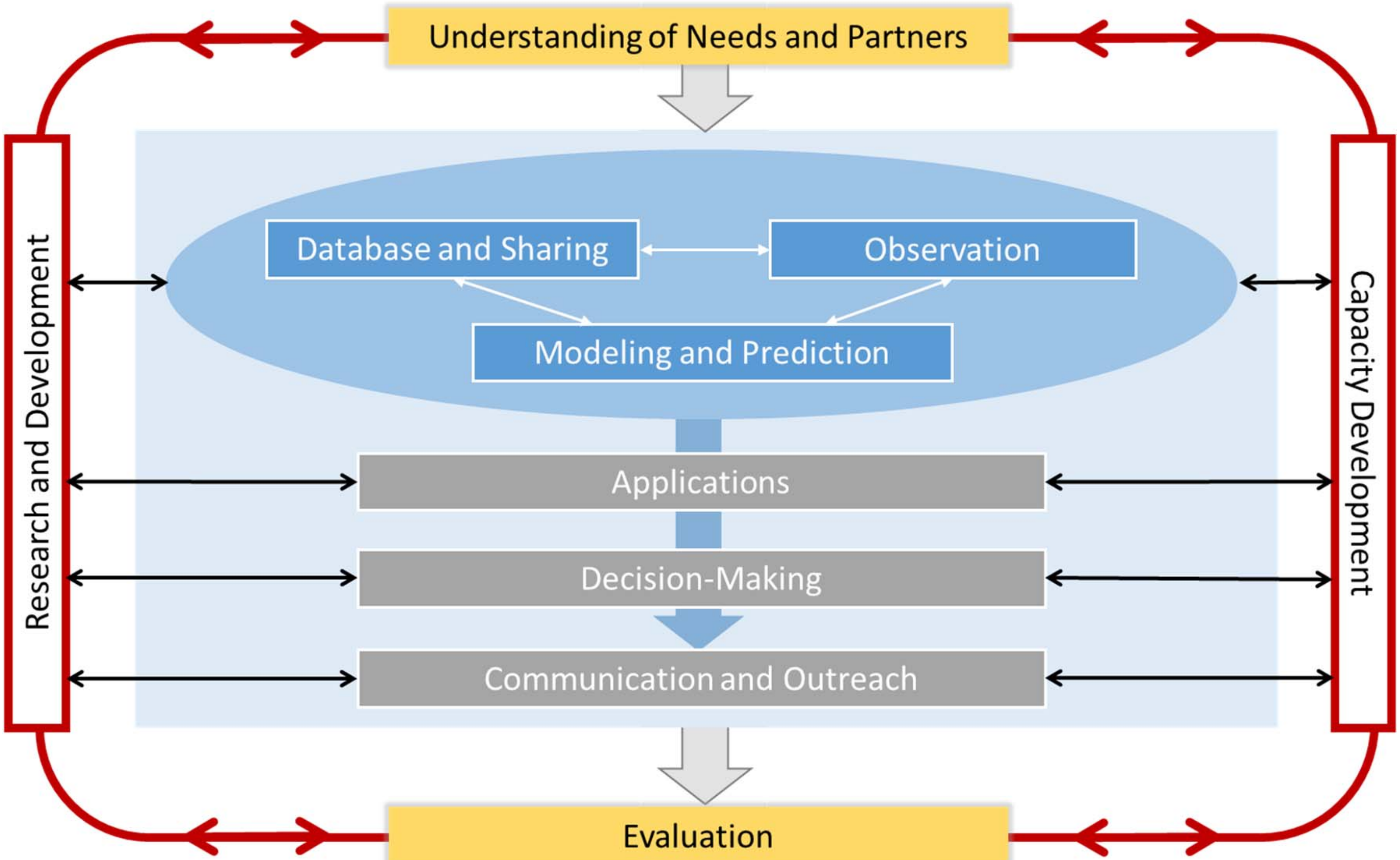
Executive Council entrusted GURME to Lead
- development of guidance on urban matters for the next Congress

Systems: interlinked

- Day-to-day operations
- Extremes



Integrated Urban, Weather, Environment, Climate, Water and related Services



WMO IUWECS Guide WT (2018); Modified from: Baklanov et al. (2017) *Urban Climate,* Grimmond et al. (2013)

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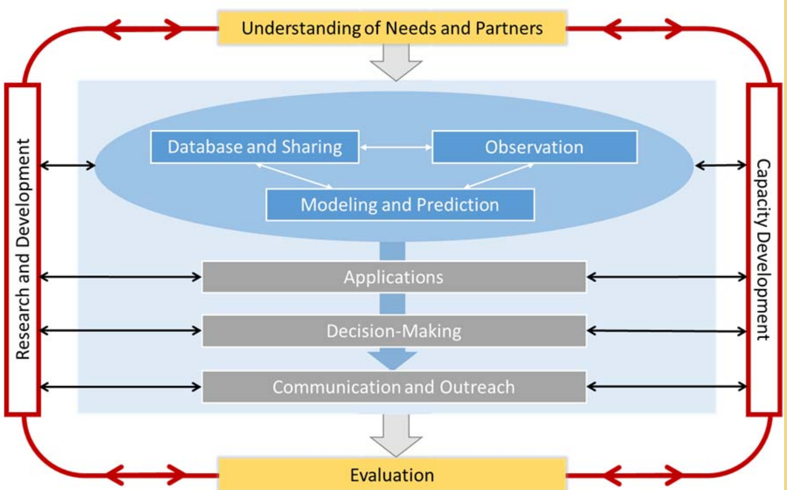

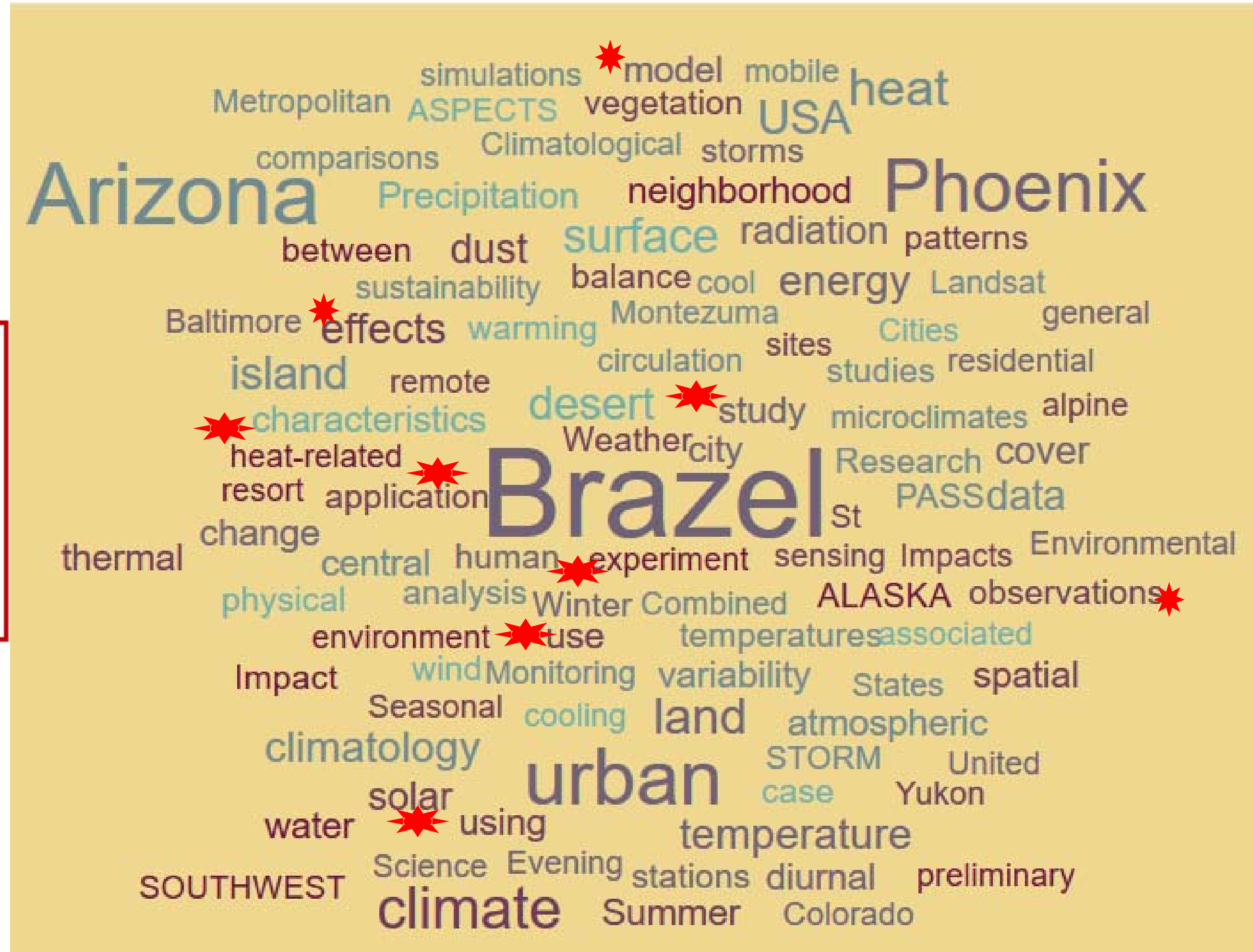

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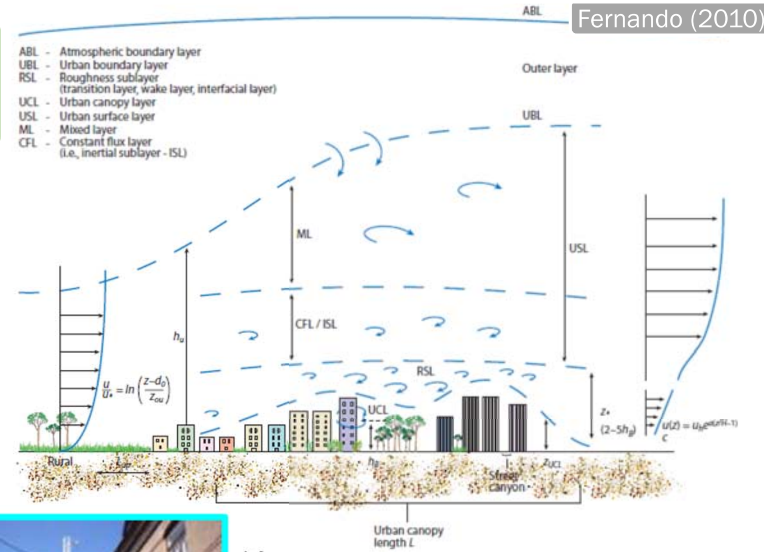
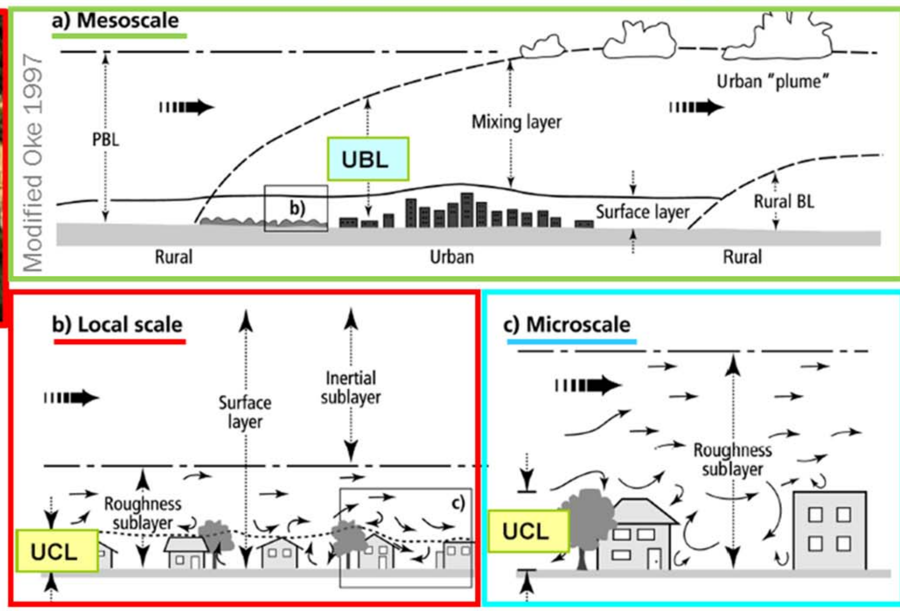
Challenge of scale

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

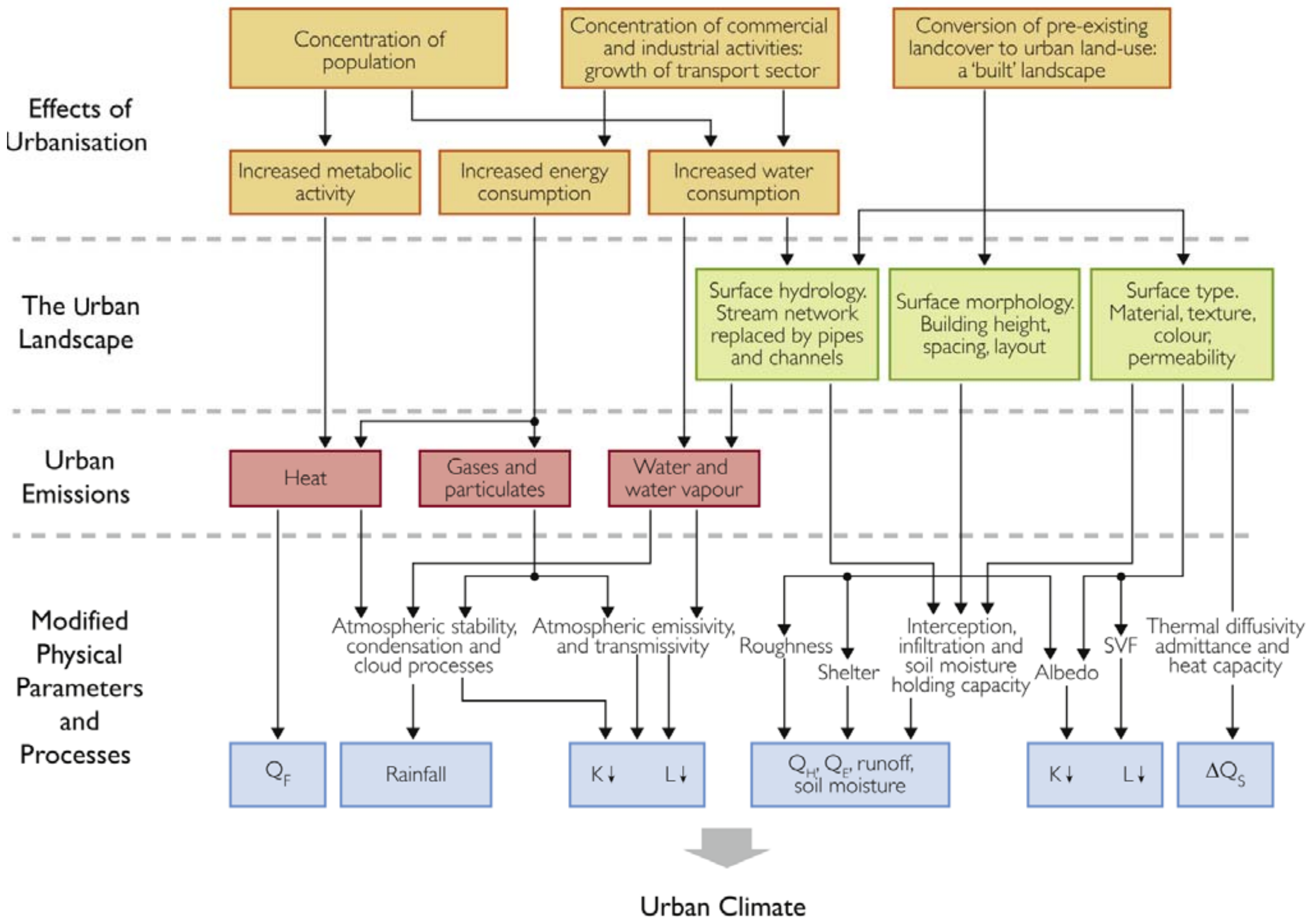




Gothenburg

Chicago

Urban Atmospheric Processes



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Cleugh and Grimmond (2012)

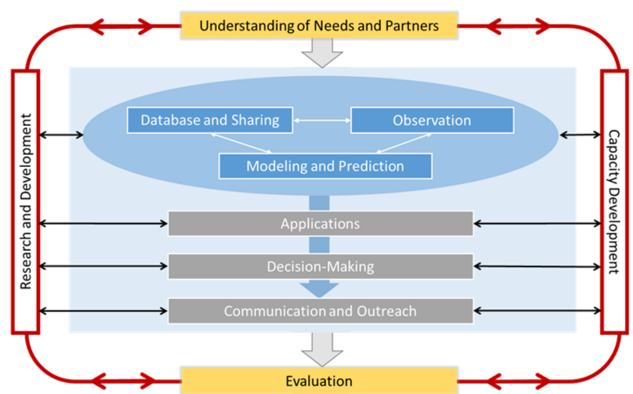
Numerous constraints

- MOST – breaks down close to the surface
- Urban roughness elements large
- Thermal 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

(Barlow et al. 2017 BAMS)

Focus

- To improve our understanding and modelling of urban surface-atmosphere processes
  - Recent work from London



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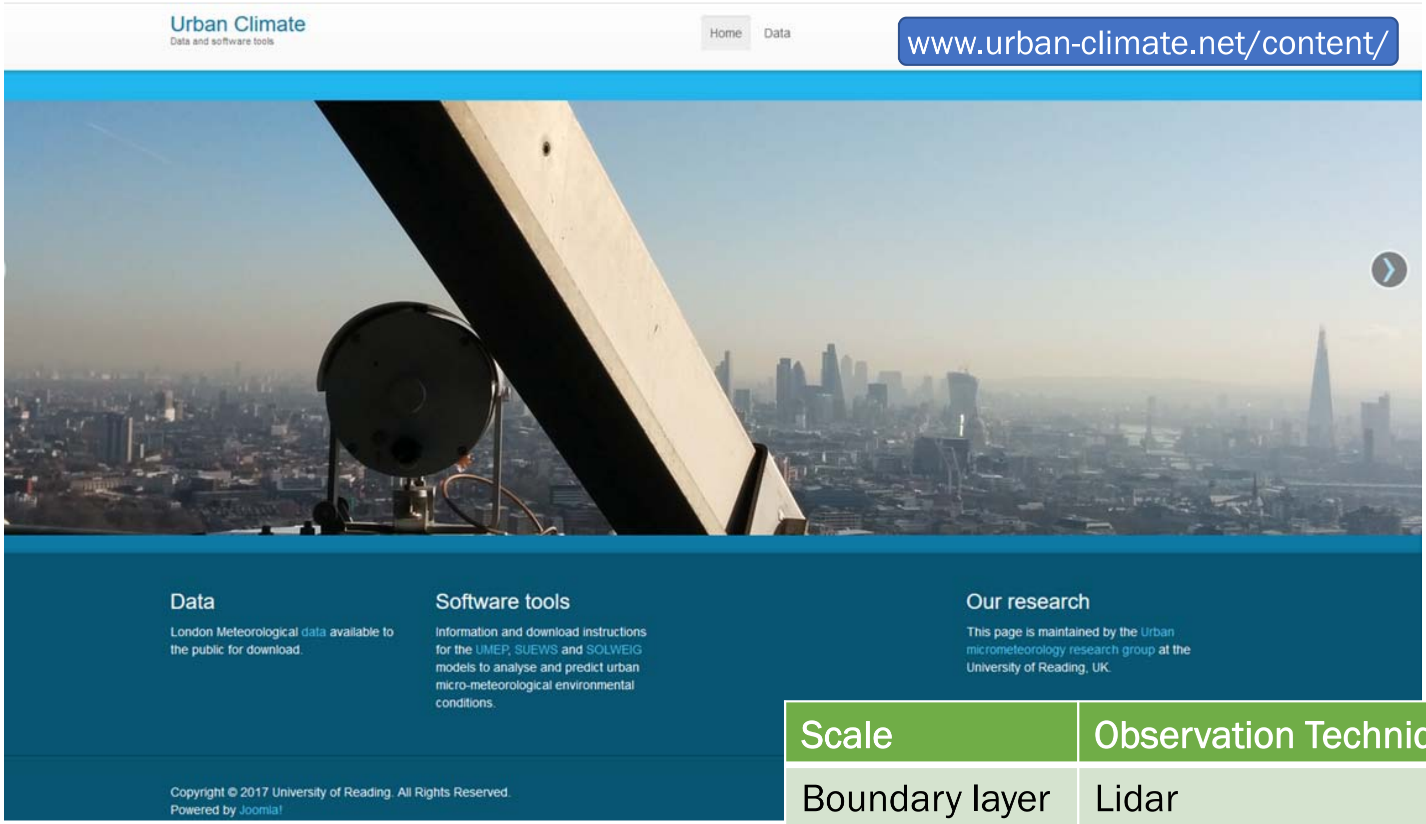

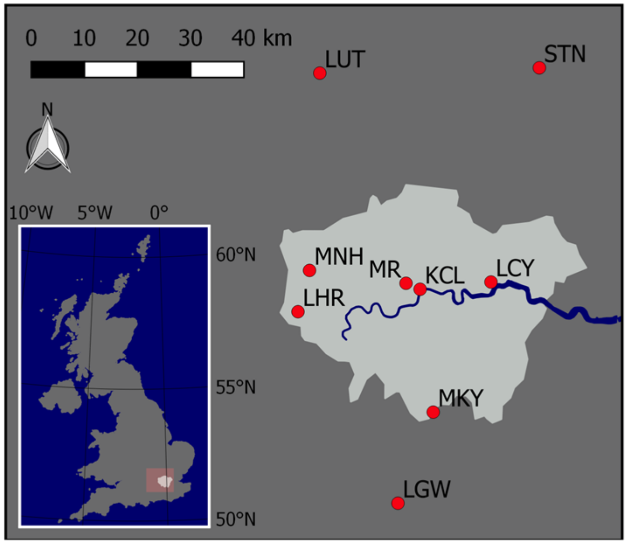

Scale	Observation Technique	Modelling
Boundary layer	Lidar	aerFO
		MLH
Neighbourhood	Scintillometry	
	EC (eddy covariance)	SUEWS
		Roughness
Canyon	Thermal IRT	DART

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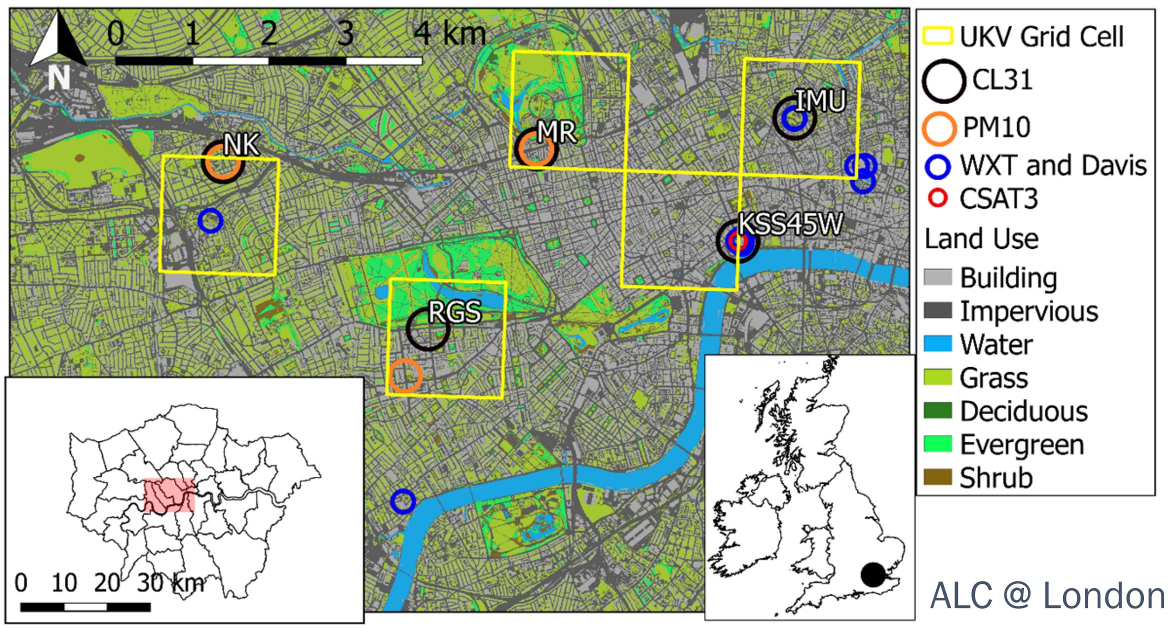
Automatic lidar ceilometer (ALC)

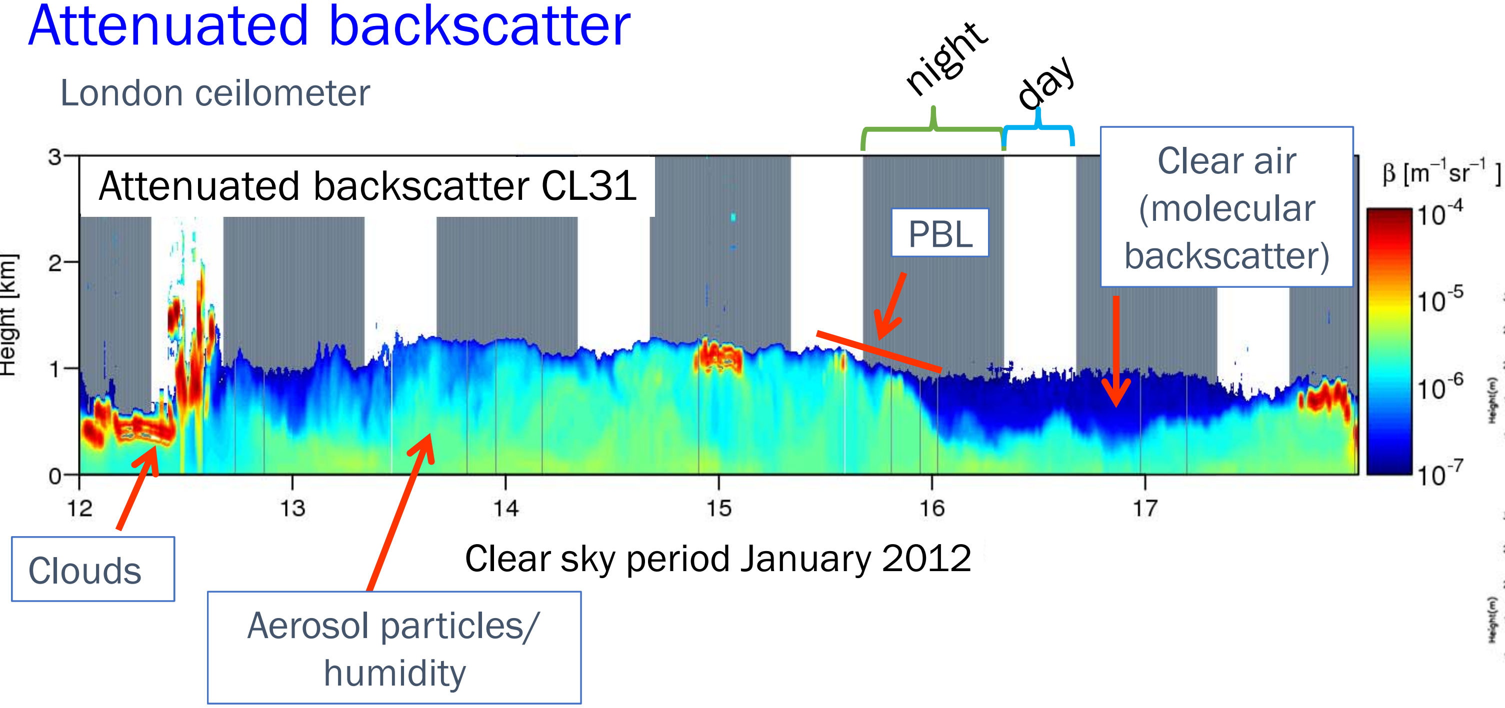
- Laser: attenuated backscatter β
  - ✓ Cloud/ice droplets
  - ✓ Aerosols
  - ✓ Molecules / atmospheric gases
  - ✓ Raw resolution: 10 m vertical, 15 s.

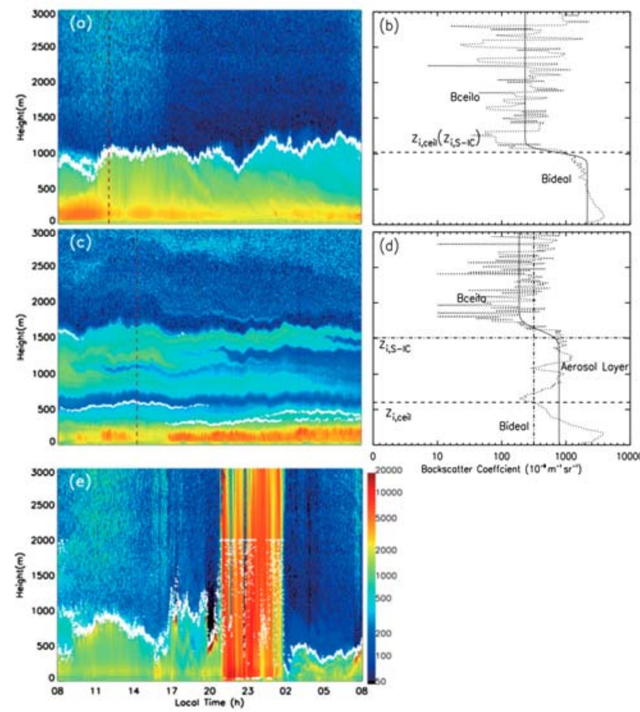


ALC @ London Air Quality Network (LAQN) site (NK)

Attenuated backscatter

London ceilometer



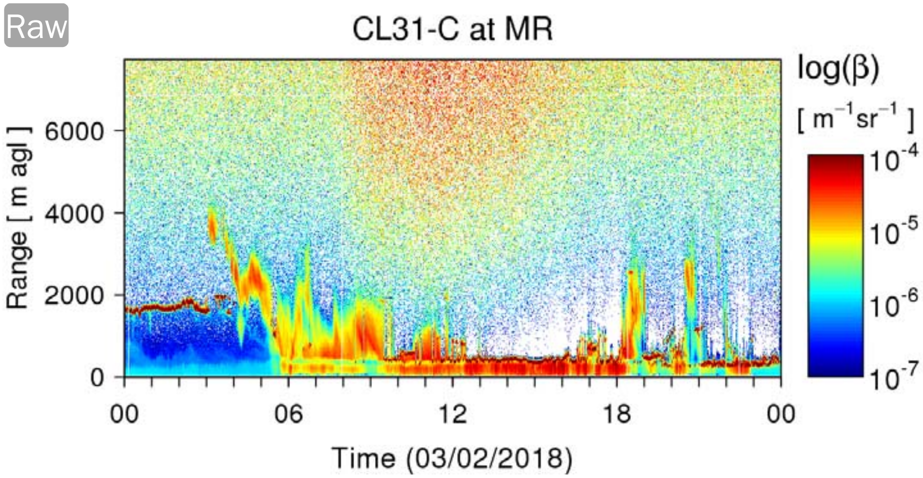


Signal:

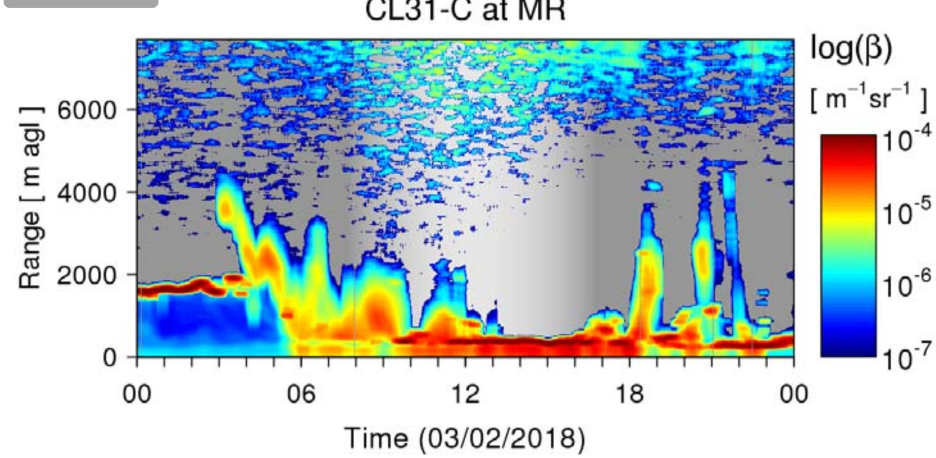
- Strong enough in PBL
- Above, only clouds (water & ice) and elevated aerosol layers detectable

Ceilometer: initial data processing

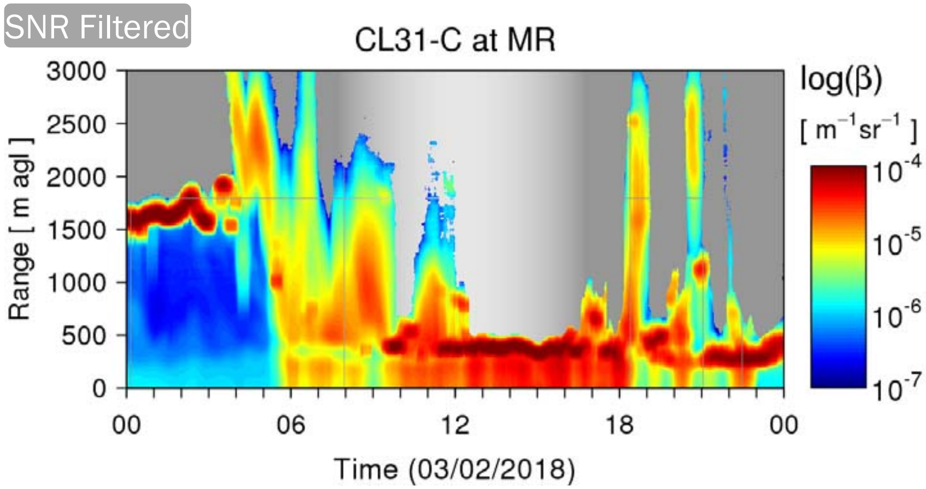
Raw



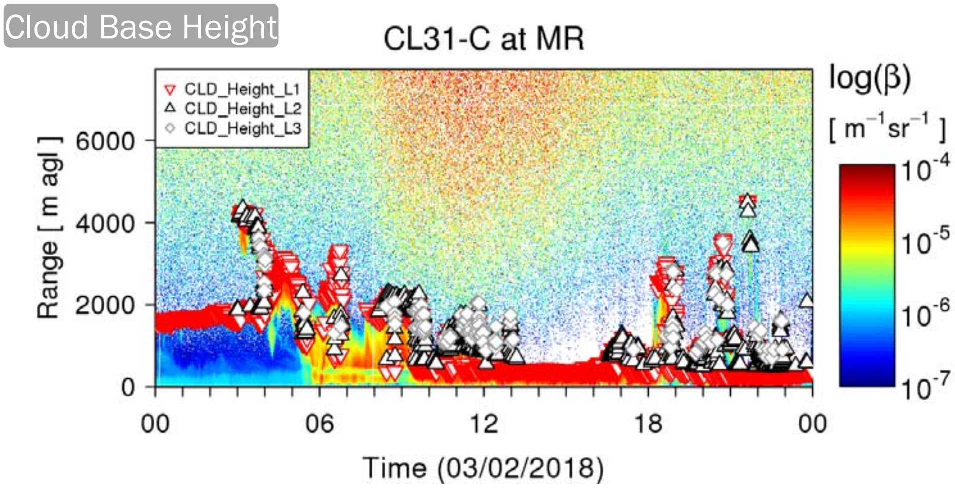
Smoothed



SNR Filtered



Cloud Base Height



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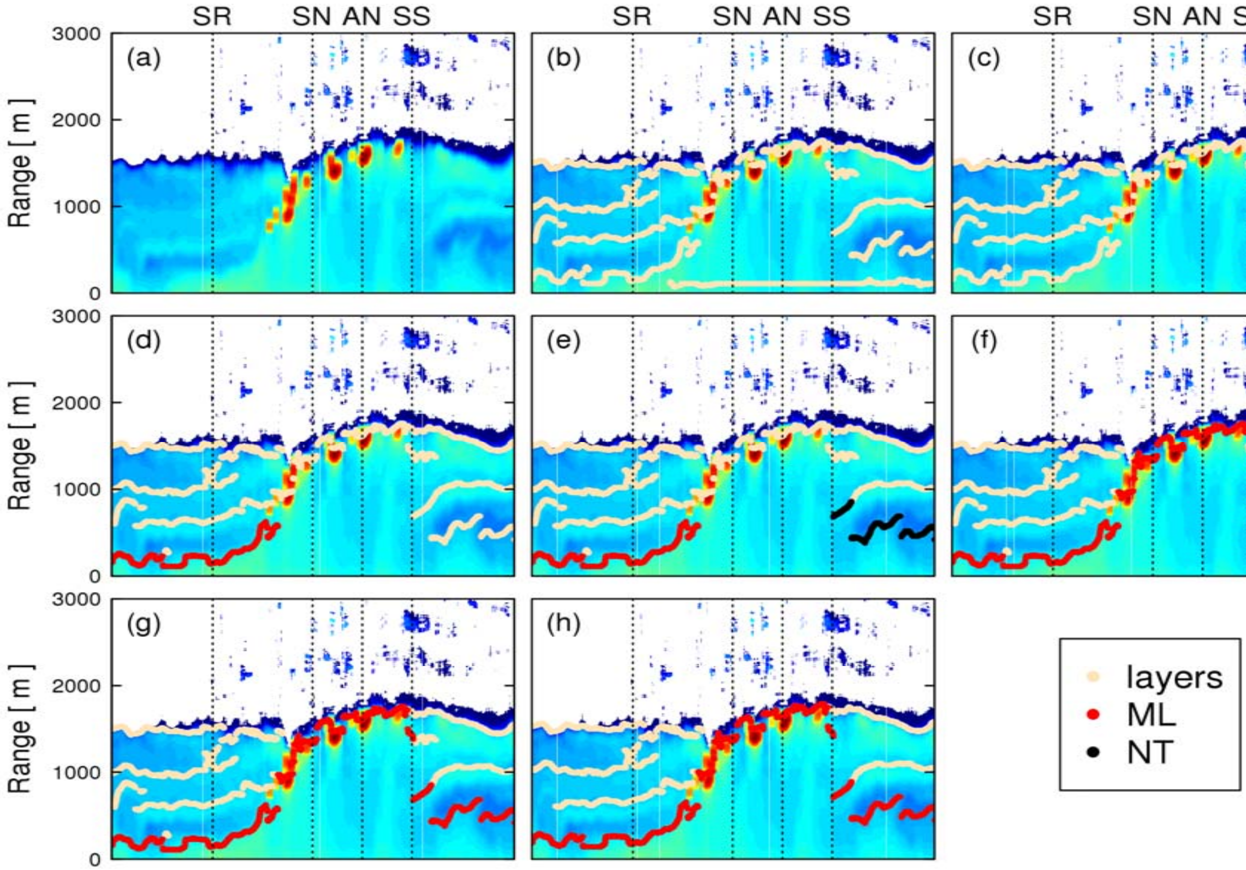
Kotthaus et al. (2016) Atmos. Meas. Tech., 9, 3769-3791 doi: 10.5194/amt-9-3769-2016

Mixed Layer Height (MLH)



CABAM

Characterising the Atmospheric Boundary layer based on ALC measurements

Algorithm to determine MLH from ALC

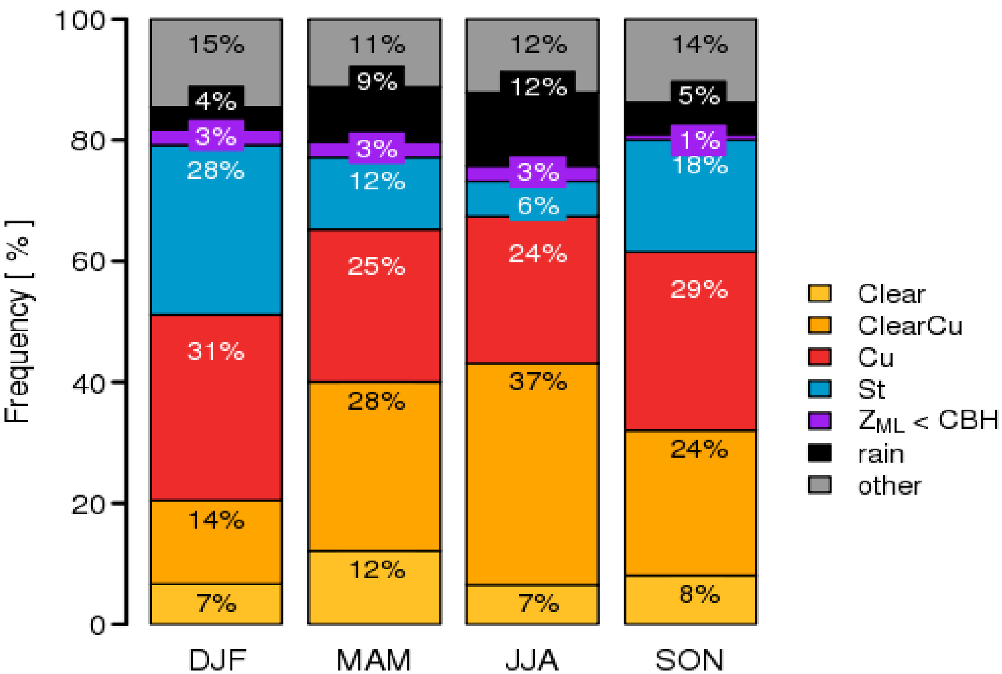
Z_{ML}

- CABAM compares well to temperature inversion heights from AMDAR profiles

AMDAR: Aircraft Meteorological Data Relay

Frequency of ABL classes: determined with CABAM

by season, 2011-2016
central London



- *clear* - conditions rare
- *Cu* - most common
- *St* - most frequent in winter
- *clearCu* - most likely in summer

Other	
Rain	complex rain patterns
Z_{ML} < CBH	Z_{ML} below ABL CBH)
St	stratiform clouds
Cu	convective clouds
ClearCu	clear night followed by Cu day
Clear	cloud-free

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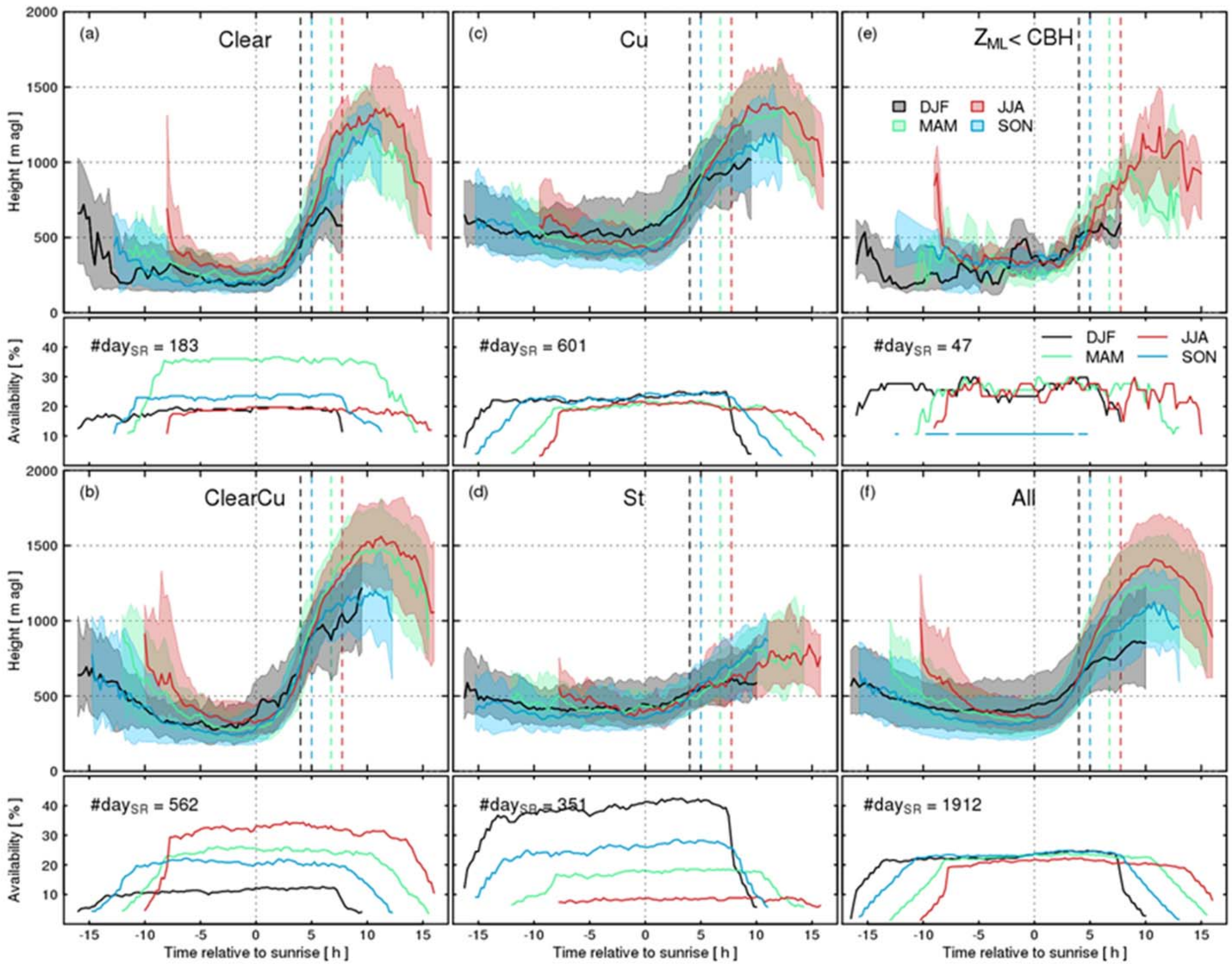
Kotthaus and Grimmond (2018b) QJRMS (mr)

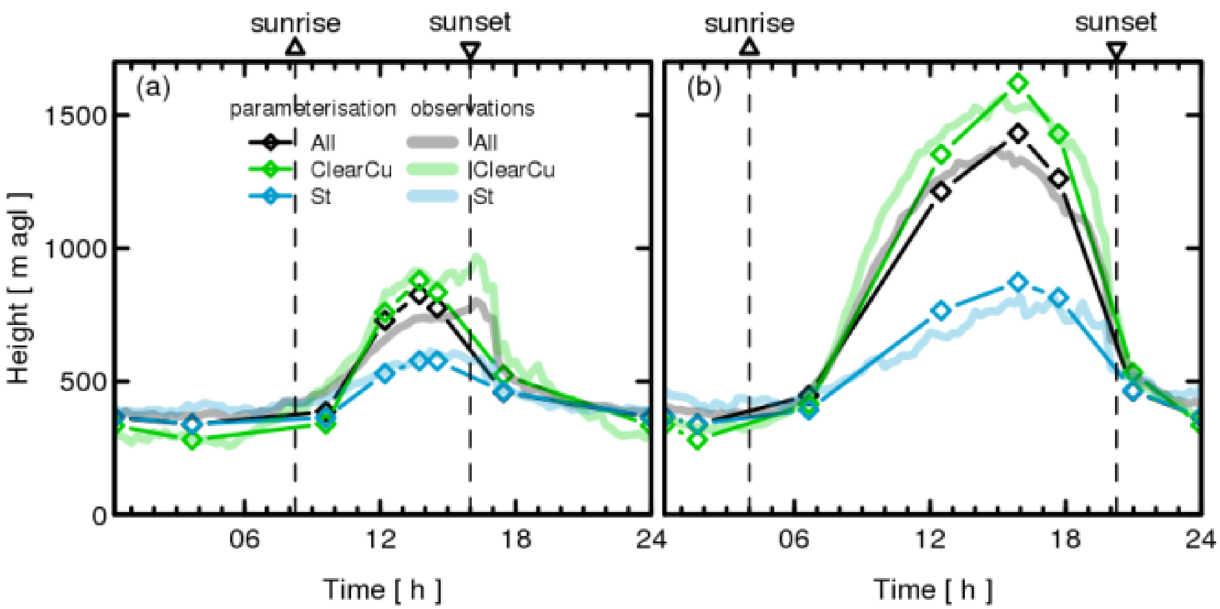
MLH Diurnal Behaviour



- Lower for clear nights
- Highest for *Cu* days
- Slightly lower if Z_{ML} < ABL cloud base
- Morning growth rates:
  - Strongest - for *ClearCu*
  - Weakest – for *St*

Kotthaus and Grimmond (2018b) QJRMS (mr)

MLH Simple parameterisation: function of cloud conditions and daylength



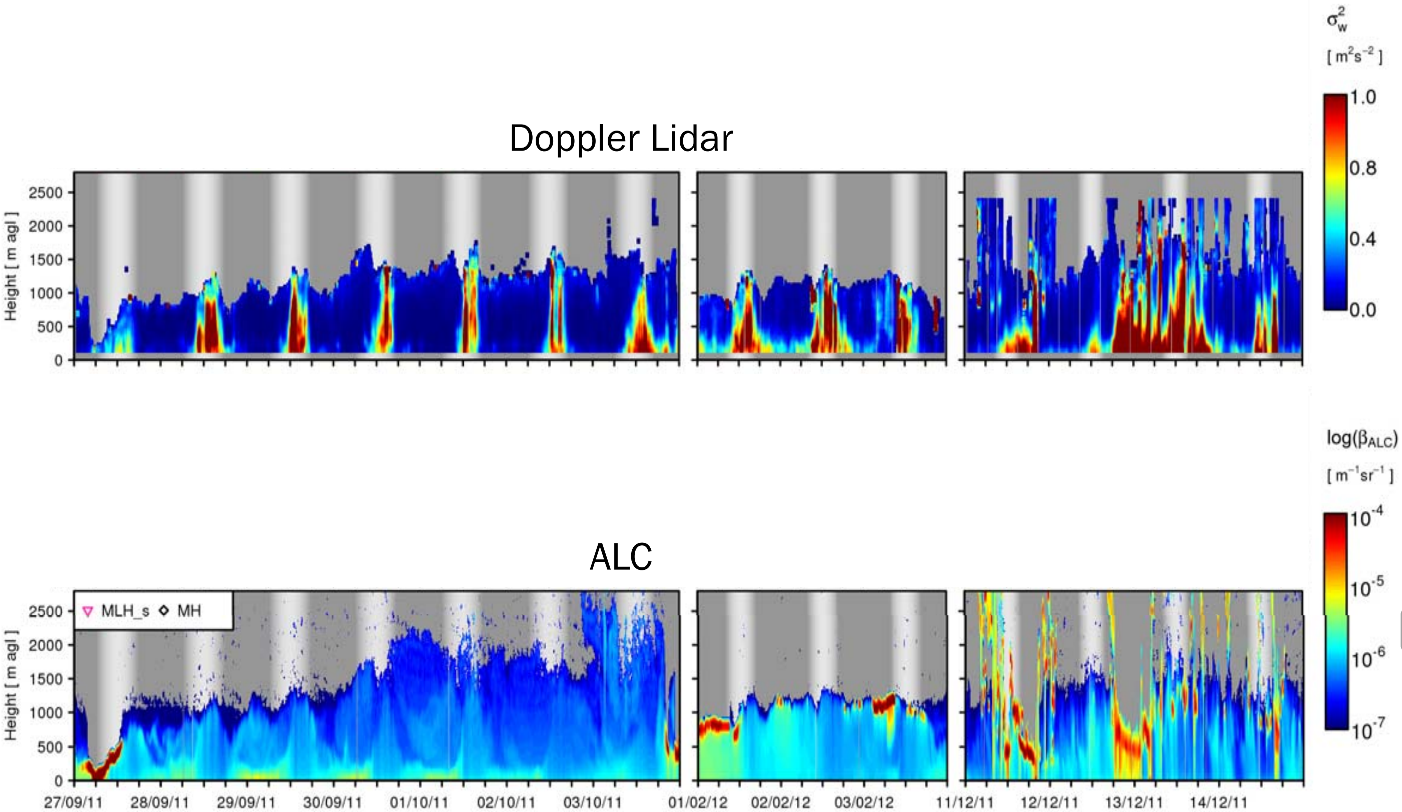
Winter solstice Summer solstice

3 months around solstices Medians 2011-2016

- Careful pre-processing of ALC data (Kotthaus et al. 2016) clearly improves aerosol-derived mixed layer height (Z_{ML}) results
- Automatic **CABAM** provides:
  - reliable Z_{ML} estimates
  - ABL classification with cloud cover & type
- London: ABL class - strong effect on Z_{ML} patterns
- Simple parameterisation based on solar position & ABL class: facilitate comparison of measurements in other cities
- Long-term urban Z_{ML} results help interpret near-surface air quality data

Kotthaus and Grimmond (2018b) QJRMS (mr)

Mixed Layer Height (MLH) and Mixing Height (MH)



Vertical velocity variance

Logarithm of attenuated backscatter

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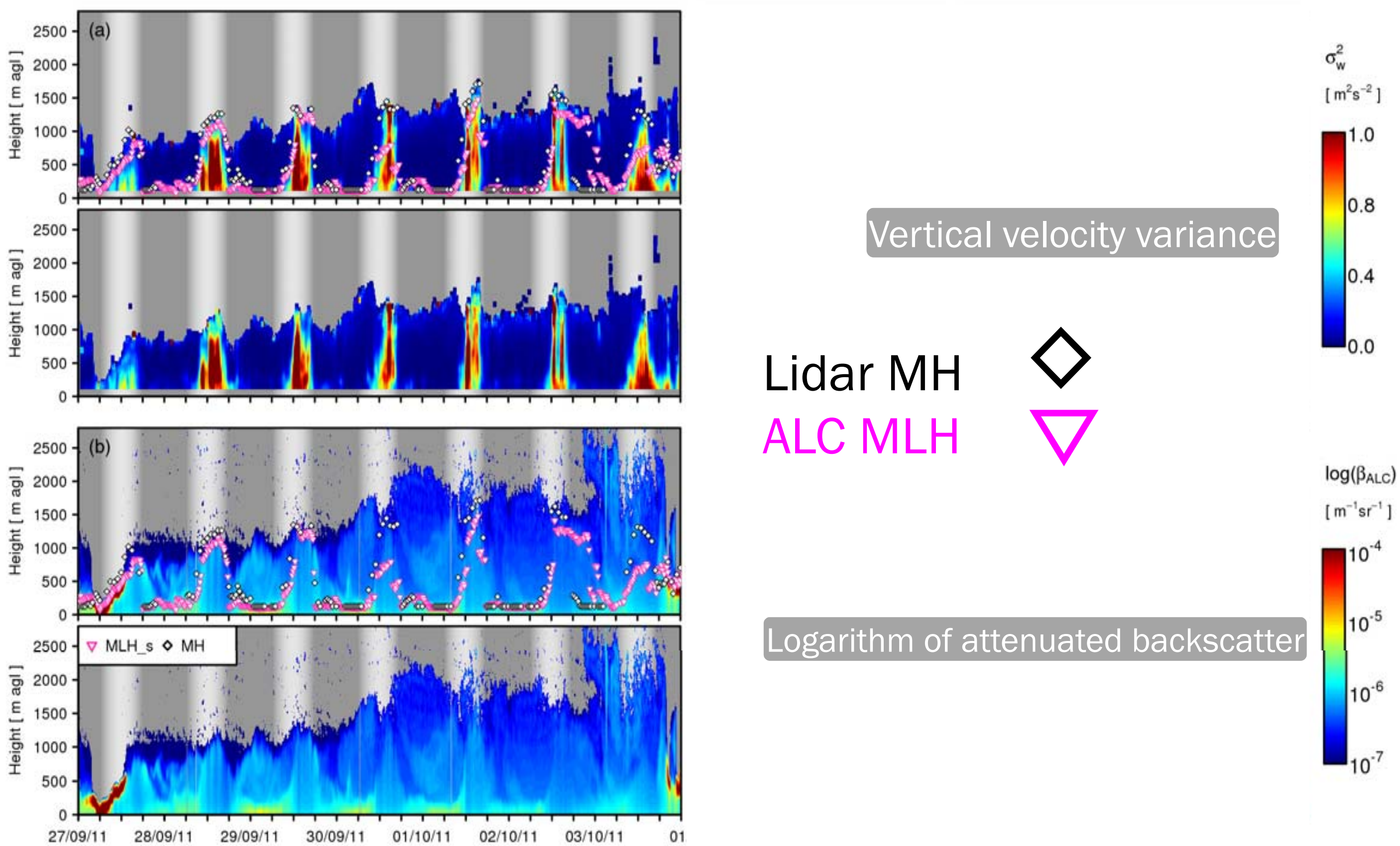
Kotthaus/Halios/Barlow/Grimmond (in prep.)

Comparison Mixed Layer Height (MLH) and Mixing Height (MH)



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Kotthaus/Halios/Barlow/Grimmond (in prep.)

Diurnal and Seasonal Cycles

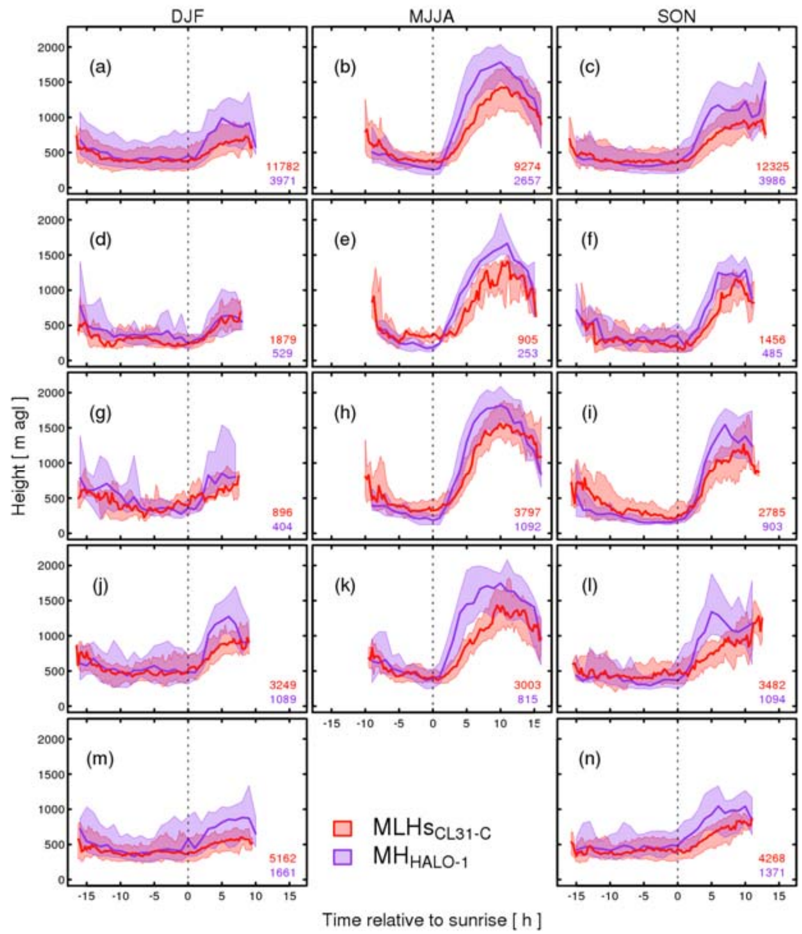
All days

Cloud-free

Clear nights followed by cloudy days

Convective cloud conditions

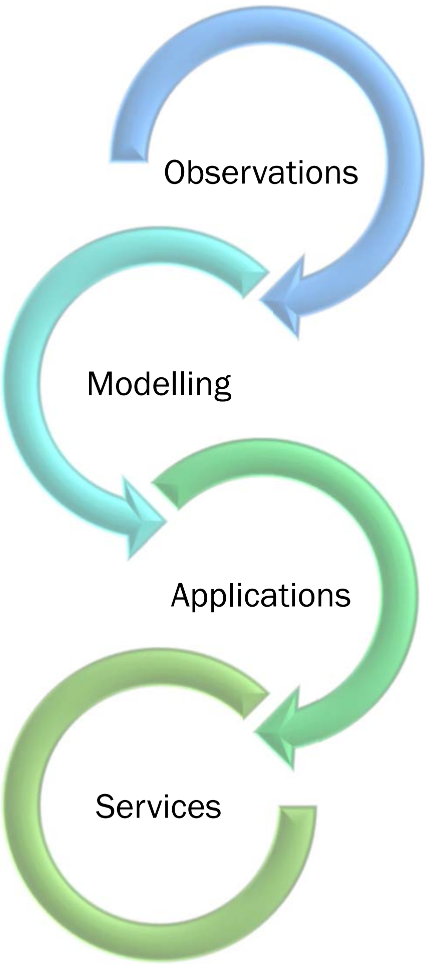
Stratiform cloud conditions

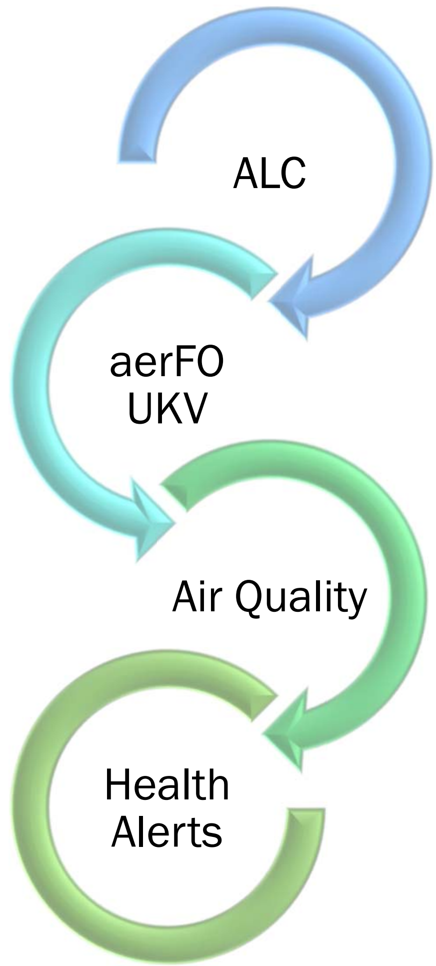


Halo Streamline
Threshold method
Barlow et al. (2011)

Vaisala CL31
CABAM algorithm
Kotthaus and Grimmond (2018a)

Data Assimilation: Forward Operator for ALC attenuated backscatter





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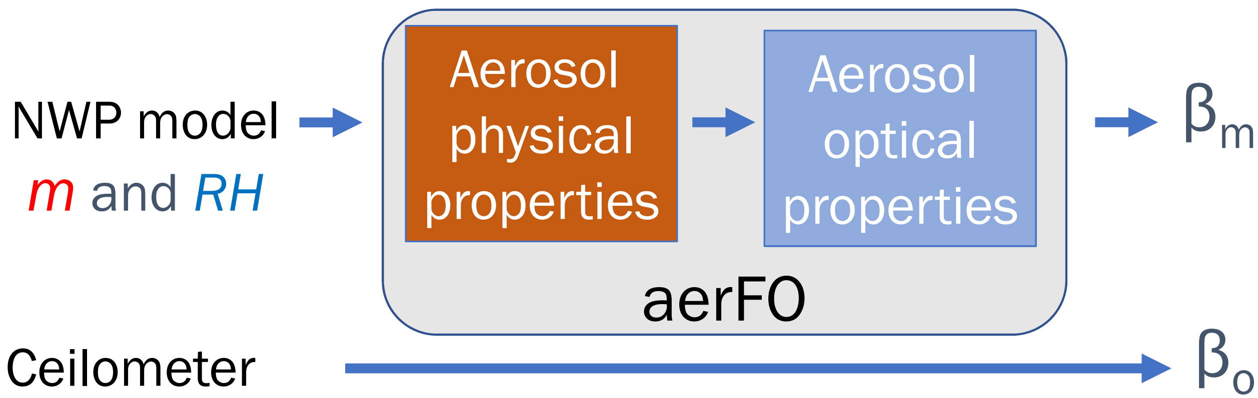
Aerosol Forward Operator (aerFO): to estimate attenuated backscatter (β_m)

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

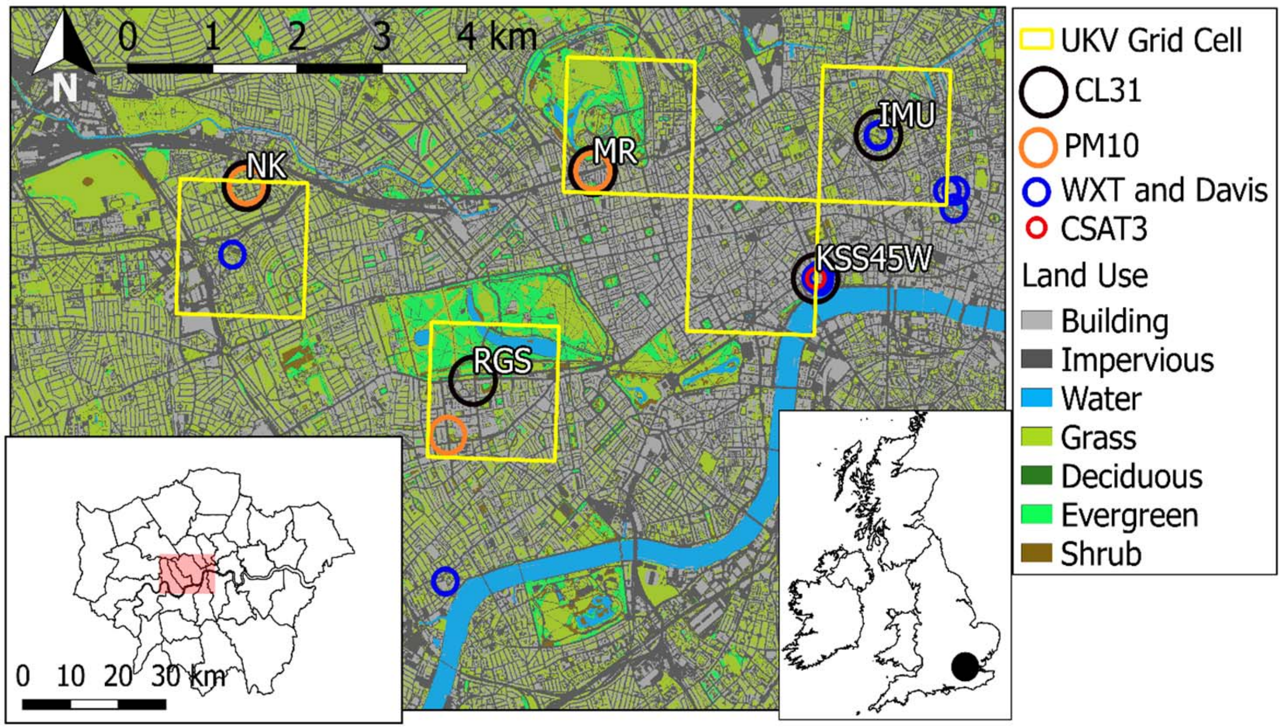
- Features:
  - Non-cloud conditions
  - Cites (AQ)
  - Wavelength dependent
  - Effect of hygroscopic growth on physical & optical properties via an extinction enhancement factor ($f_{RH,ext}$)
    - Includes effect of water vapour absorption

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



NWP and observation data

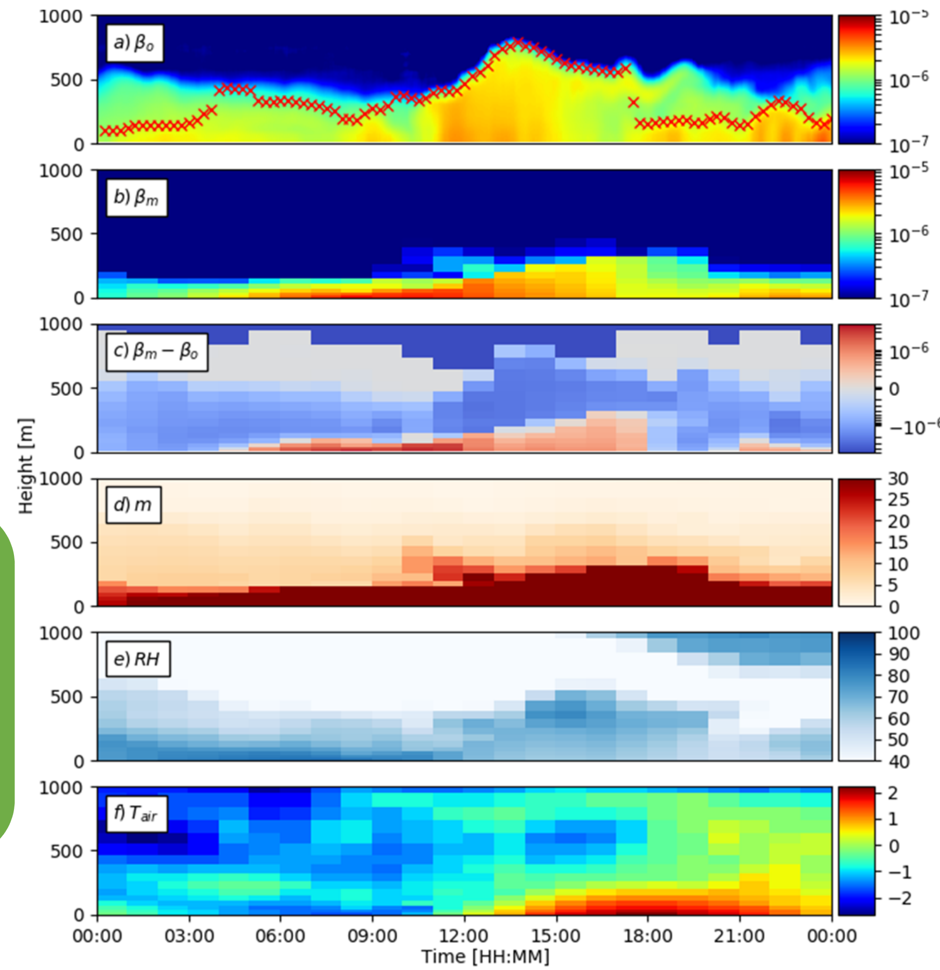
- 11 clear sky days between 5 Feb 2015 and 31 Dec 2016.
- NWP: **Met Office UKV** 1.5 km 21Z forecasts (3 h spin up, 1 h resolution)
- Observation: 4 Vaisala CL31 ceilometers (raw resolution 10 m vertical, 15 s)
  - Processed: moving average (25 min, 110 m, Kotthaus et al., 2016) and calibrated (Hopkin et al., in prep).



Warren et al. (in review)

High pollution case (19 January 2016)

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



Observed β

Modelled β

$\beta_m - \beta_o$

Aerosol mass

RH

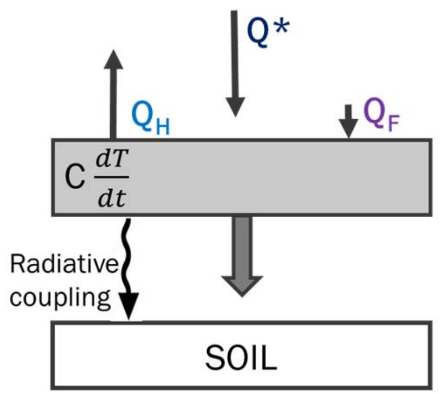
T_{air}

- 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

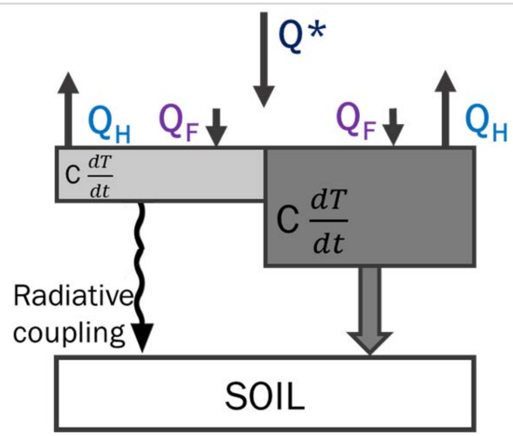
Warren et al. (in review)

To improve mixing new urban land surface scheme in UKV

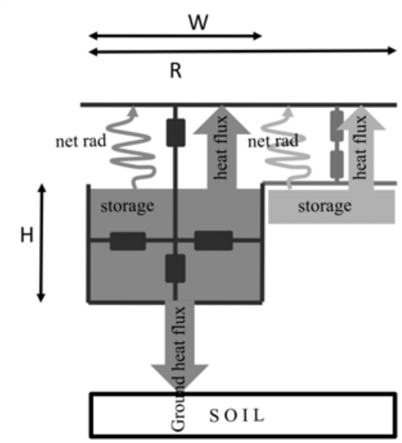
	Best 1 - Tile	MORUSES
Surface	1 bulk	Canyon and roof
Q^*	Bulk α and ε	Material properties with form
Q_F	Prescribed	
Q_E	Non-urban tile	
Q_H	Thermal roughness length	Resistance network
$C\frac{dT}{dt}$	1 component	2 components



Best et al. (2004)



Harman and Belcher (2006)
Porson et al. (2010)

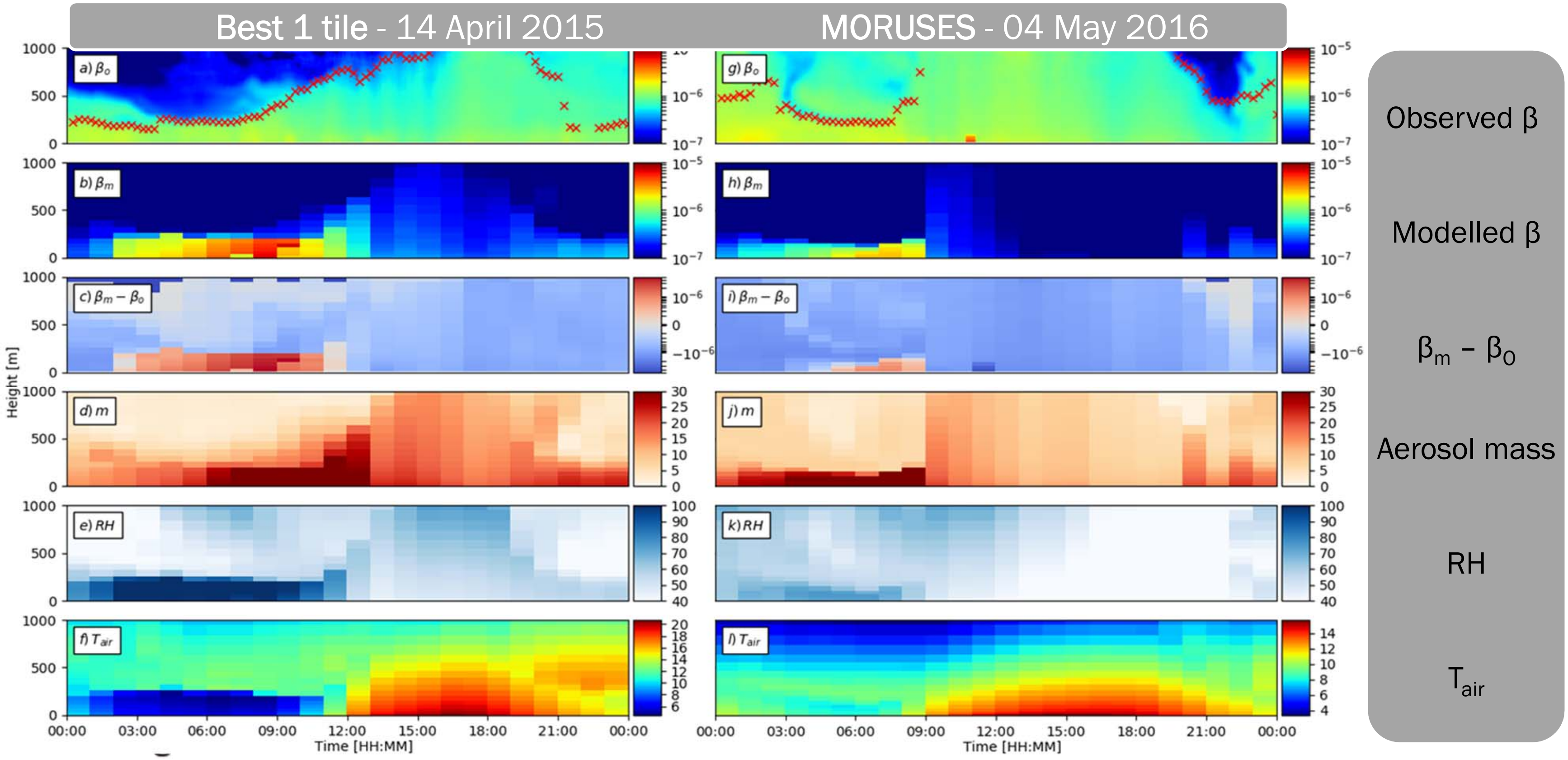


Bohnenstengel et al. (2011)

Impact of changing model dynamics on β_m as

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

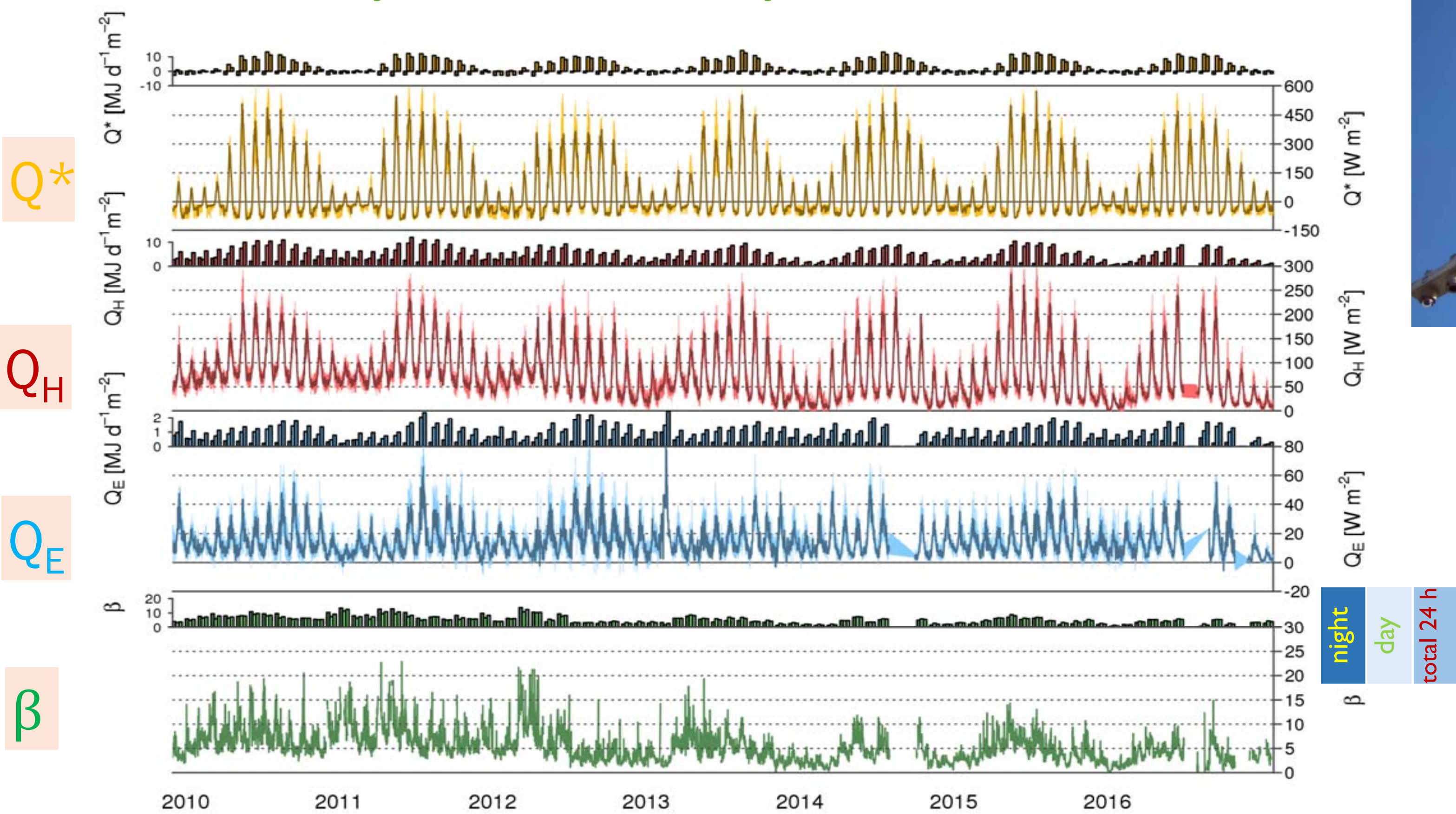
- Morning near-surface β_m
  - 1-tile - high throughout
  - MORUSES – less
- Cold surface bias →delayed vertical mixing of m_{MURK} and high RH

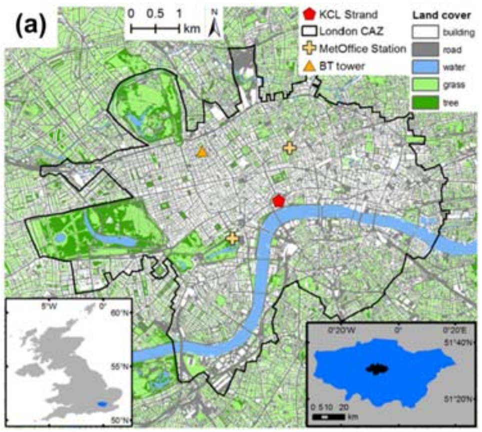


Warren et al. (in review)

Fluxes: EC - long term measurements

Monthly Median Diurnal Cycle, shaded IQR, KSS

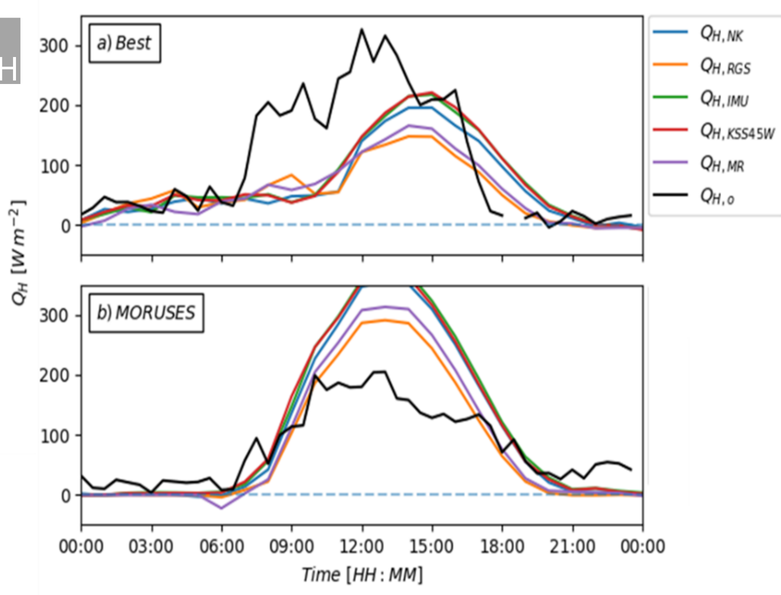


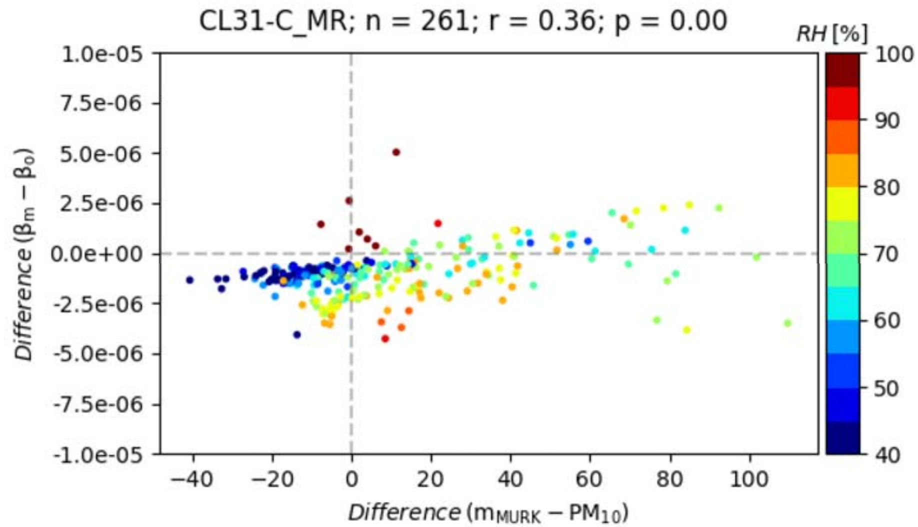


Kotthaus & Grimmond (2014a) Urban Climate, Kotthaus and Grimmond (in prep).

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 $f_{RH,ext}$

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Warren et al. (in review)

www.urban-climate.net/content/

Urban Climate
Data and software tools

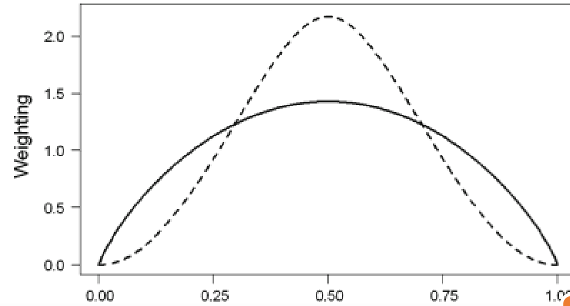
Home | Data | Data and Observation

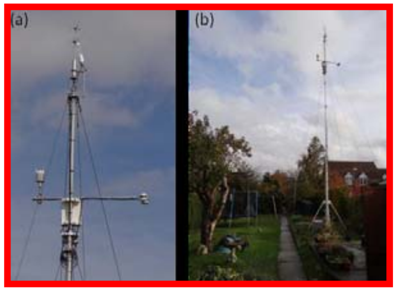
Data
London Meteorological data (LUMA and Southwark).

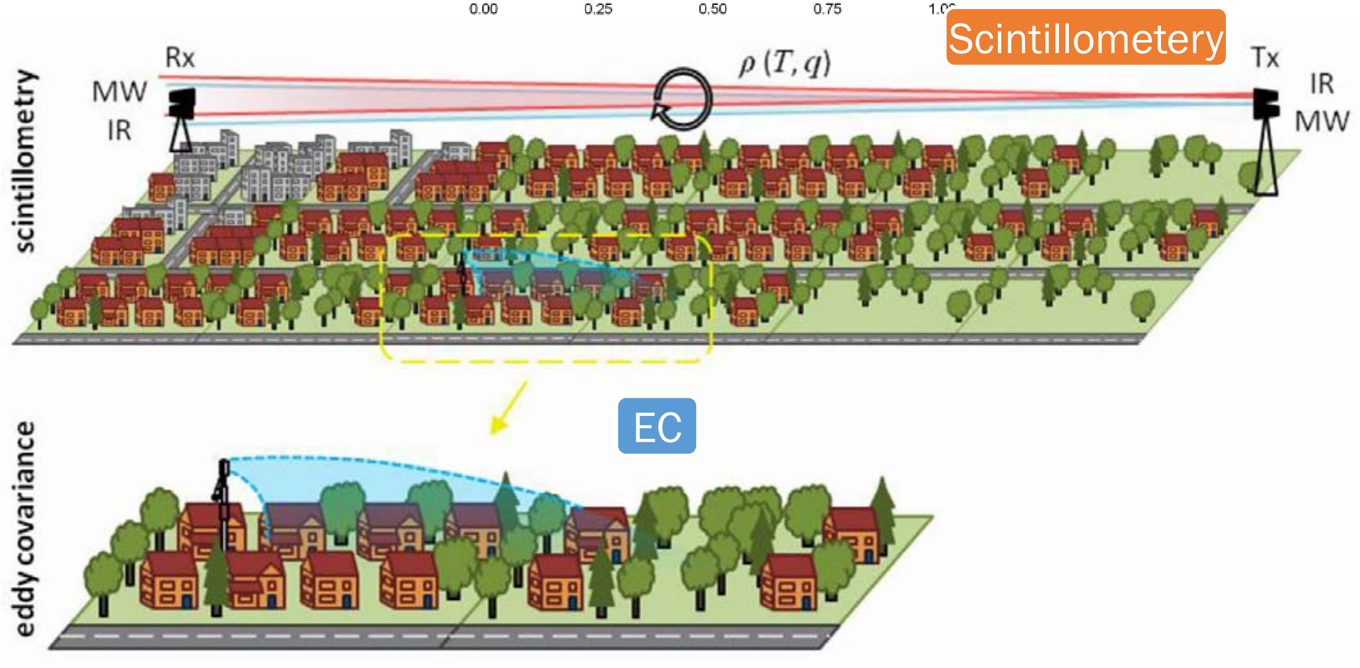
Software tools
Information and download instructions for the UMEP, SUEWS and SOLWEIG models to analyse and predict urban micro-meteorological environmental conditions.

Our research
This page is maintained by the Urban micrometeorology research group at the University of Reading, UK.

Scintillometry – another technique for turbulent heat fluxes

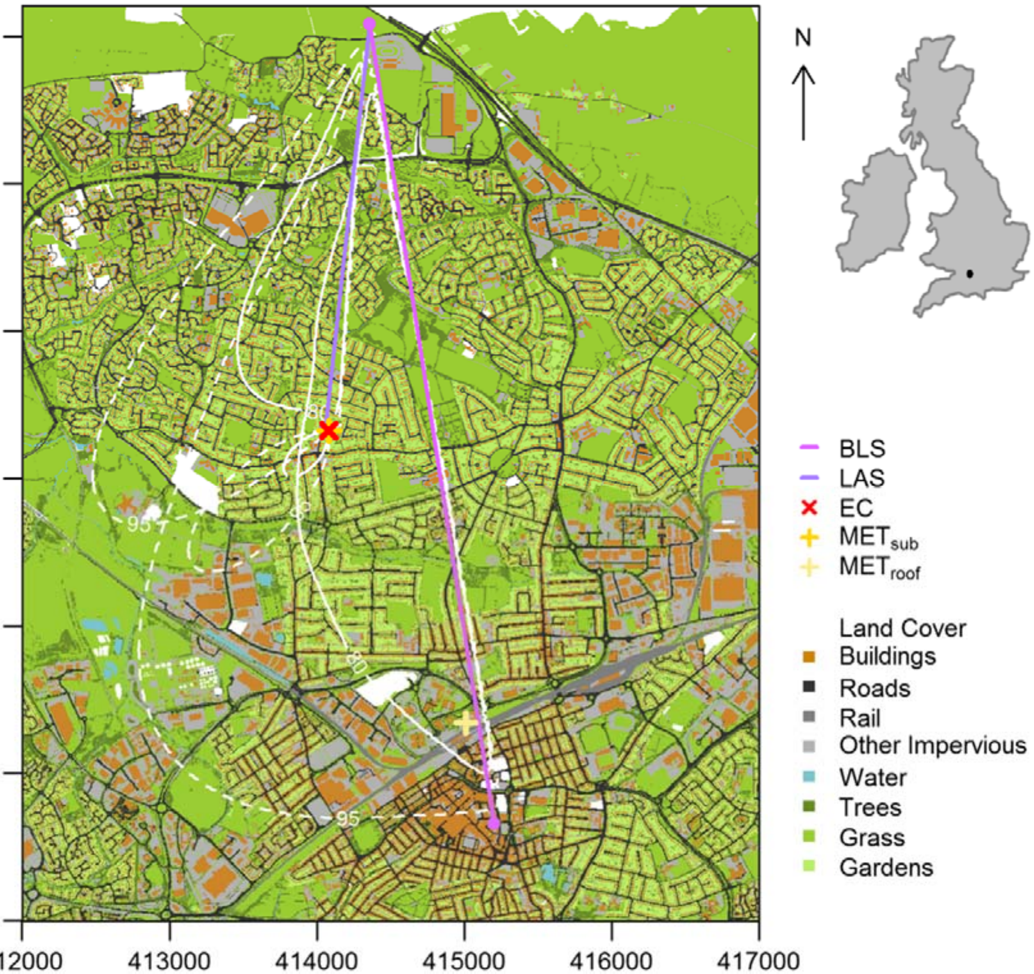






Ward et al. (2011) BLM; Ward (2013)

Multi-scale Measurements of Q_H



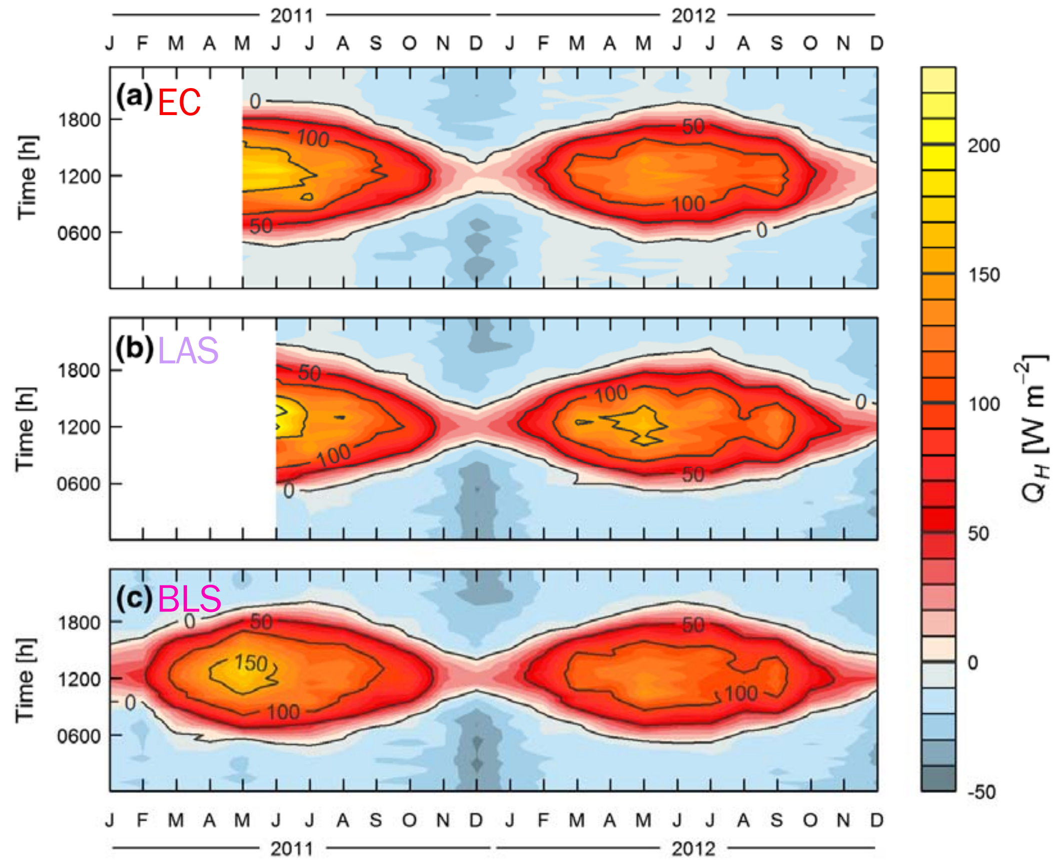
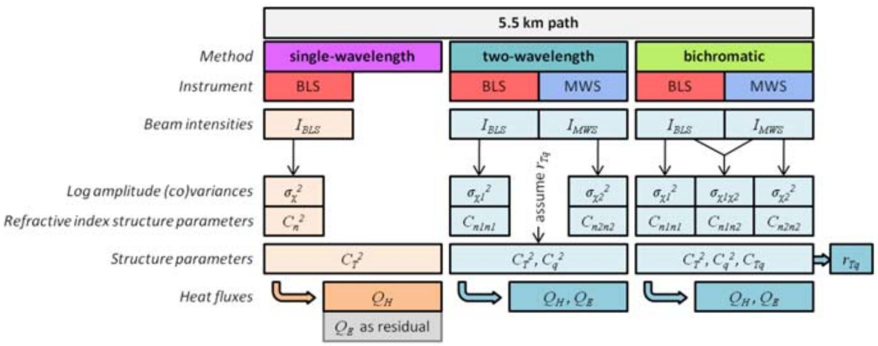
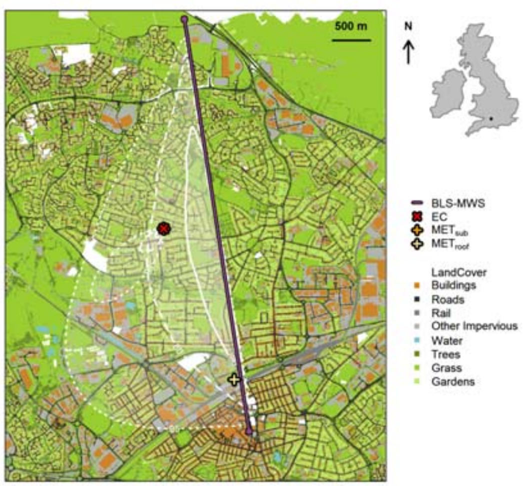


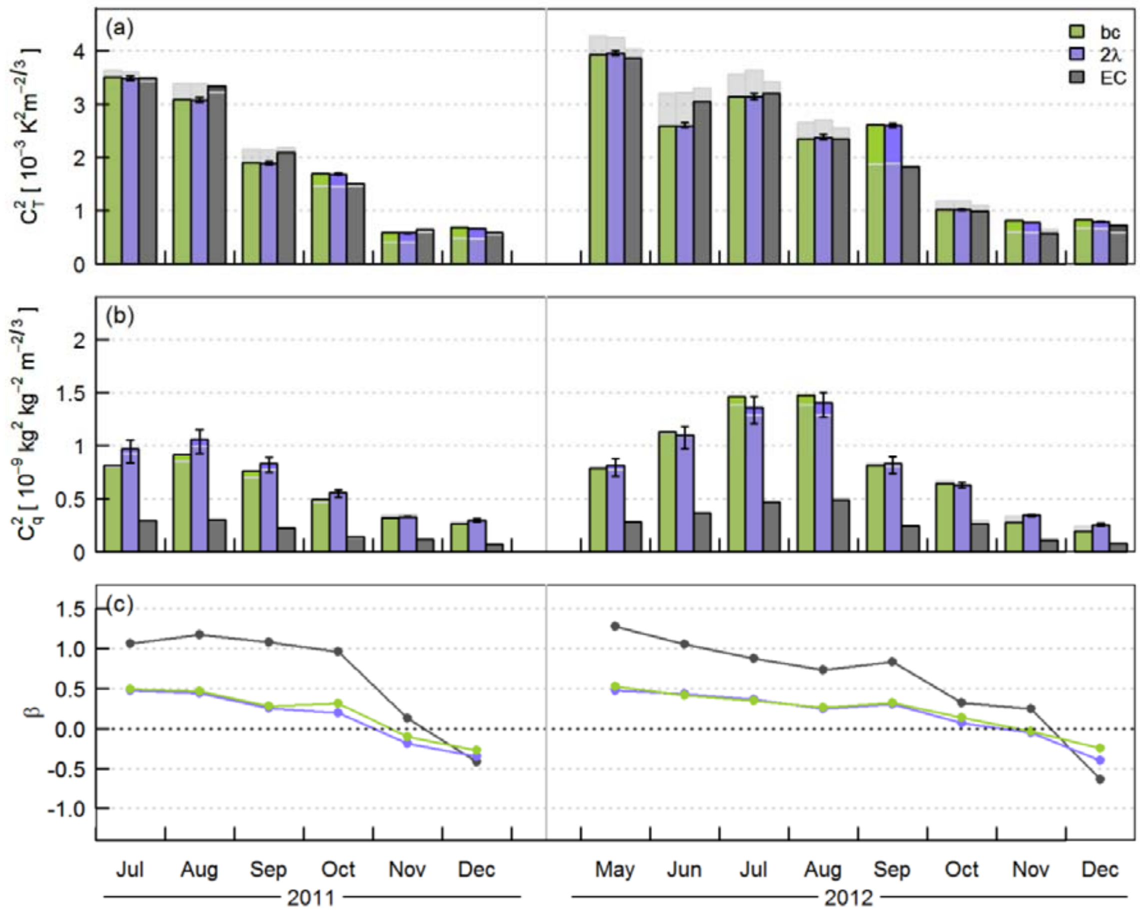
Fig. 4 Temporal variation of monthly mean diurnal cycles of sensible heat fluxes from (**a**) eddy covariance, (**b**) the LAS and (**c**) the BLS

Ward et al. (2014) BLM

Infrared and Millimetre-wave Scintillometry (sensible and latent heat fluxes)

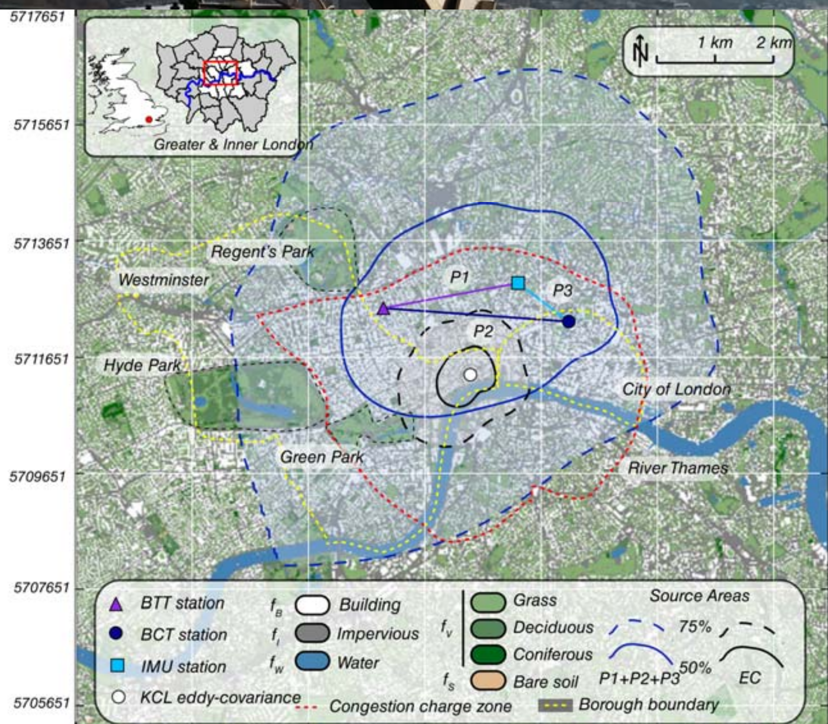


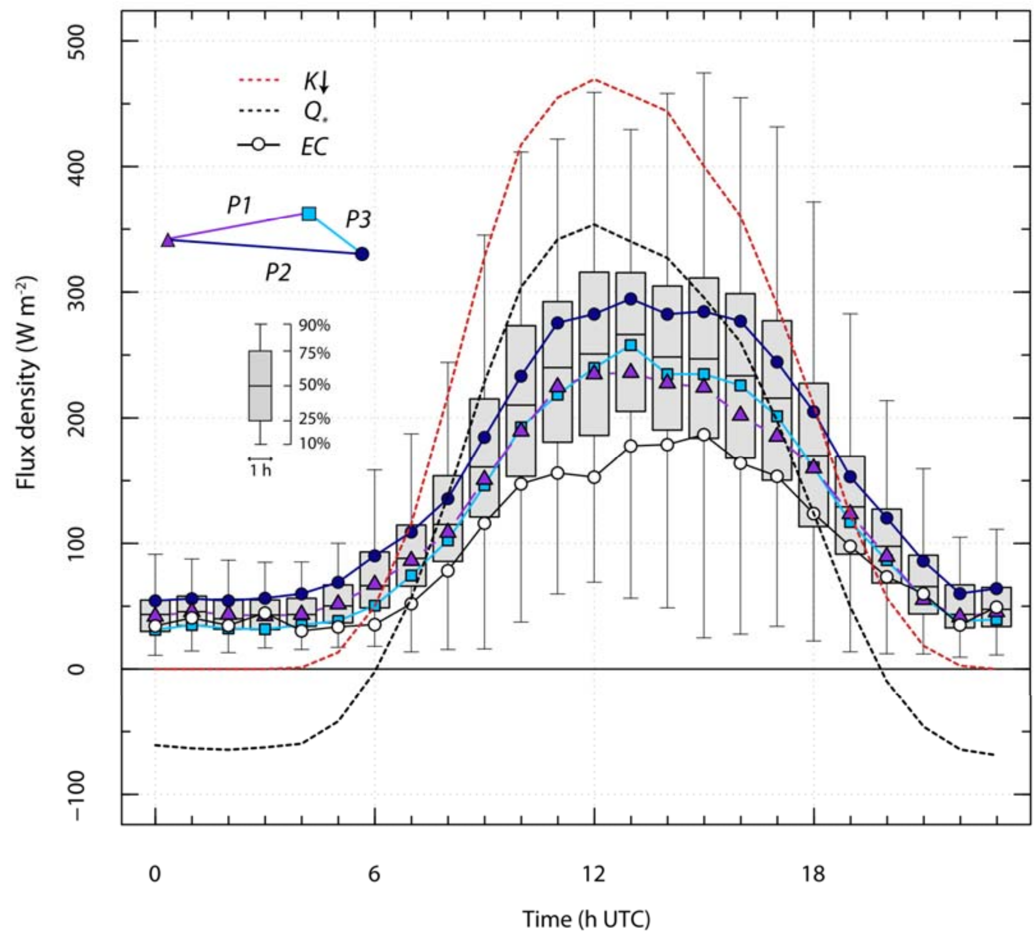




Ward et al. (2015a) Atmos. Meas. Tech., 8, 1385–1405 doi:10.5194/amt-8-1385-2015

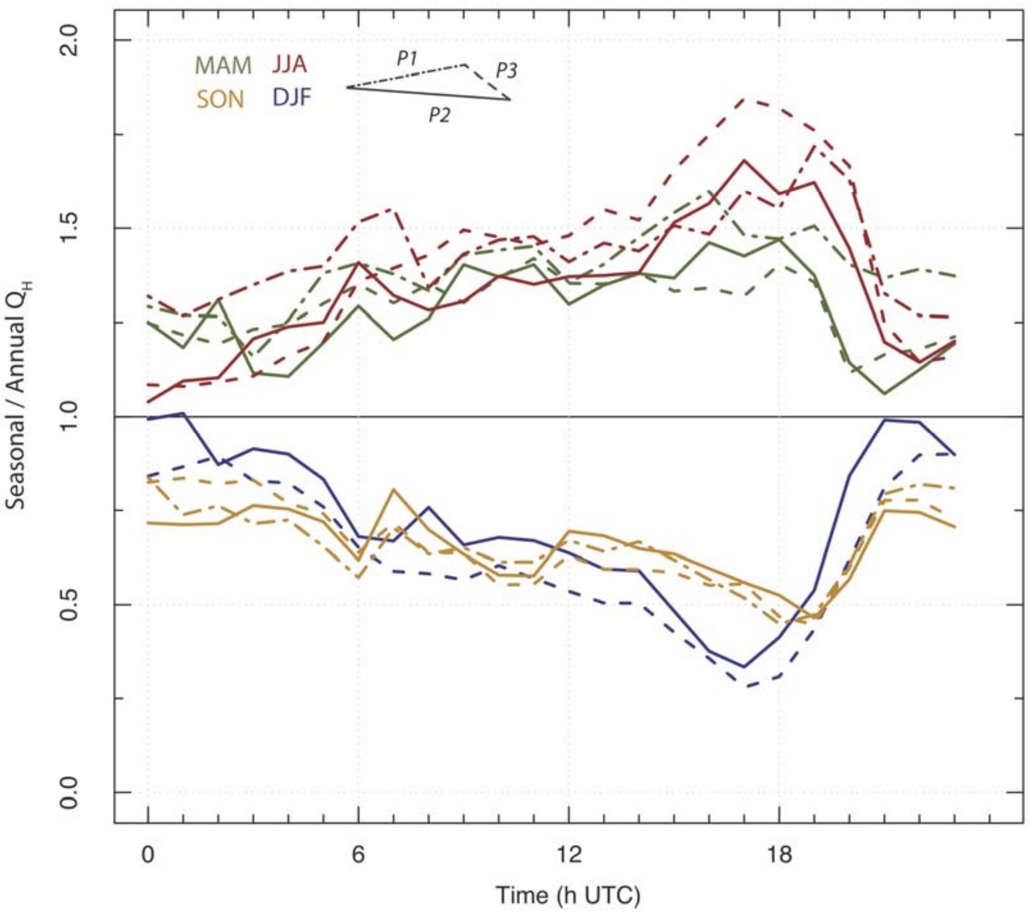
Sctinillometry – 3 paths (London)

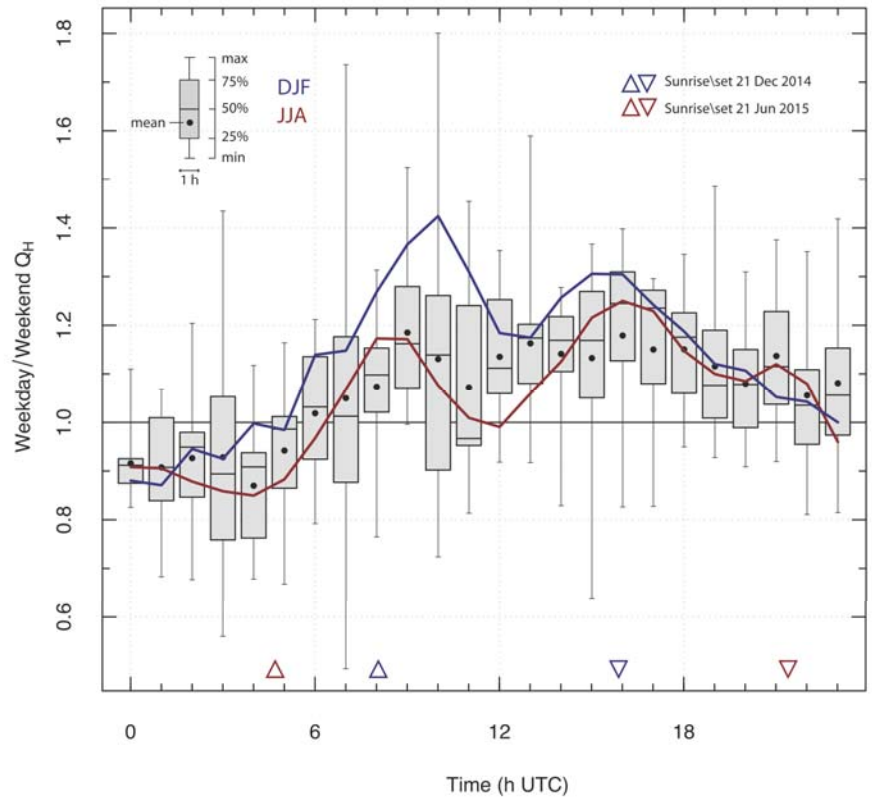




Crawford et al. 2017 QJRMS doi:10.1002/qj.2967

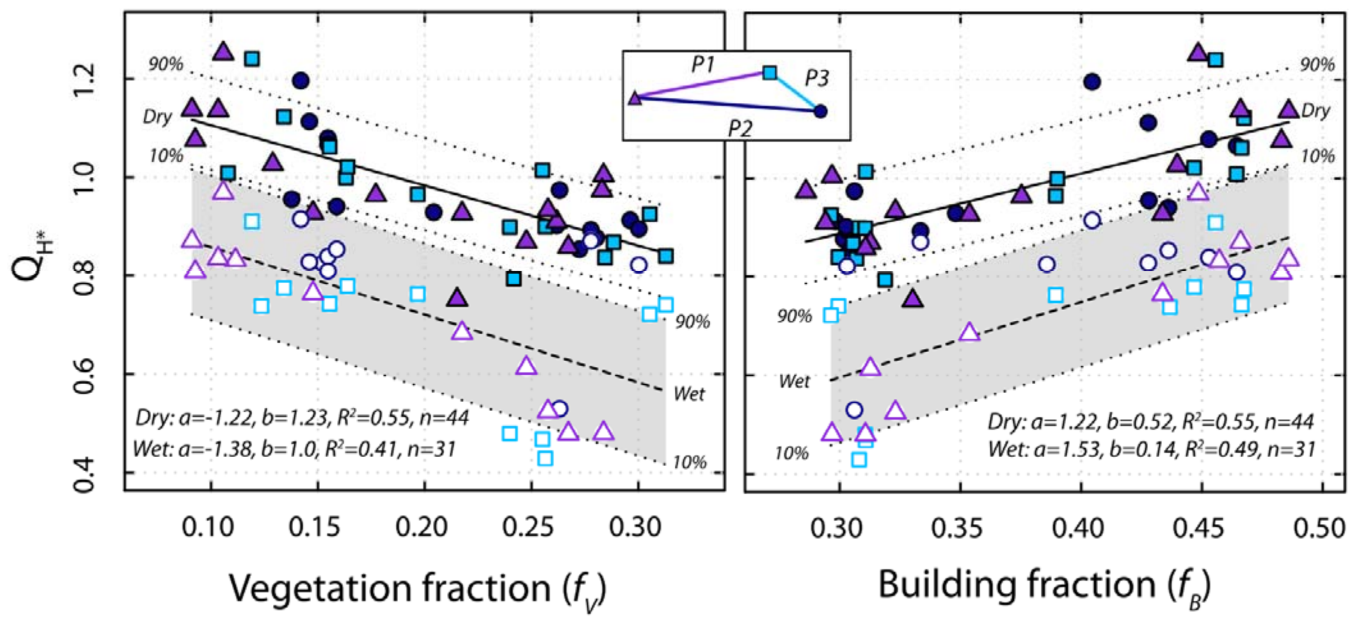
Spatial Variability with Season by time of day -------- and day of week





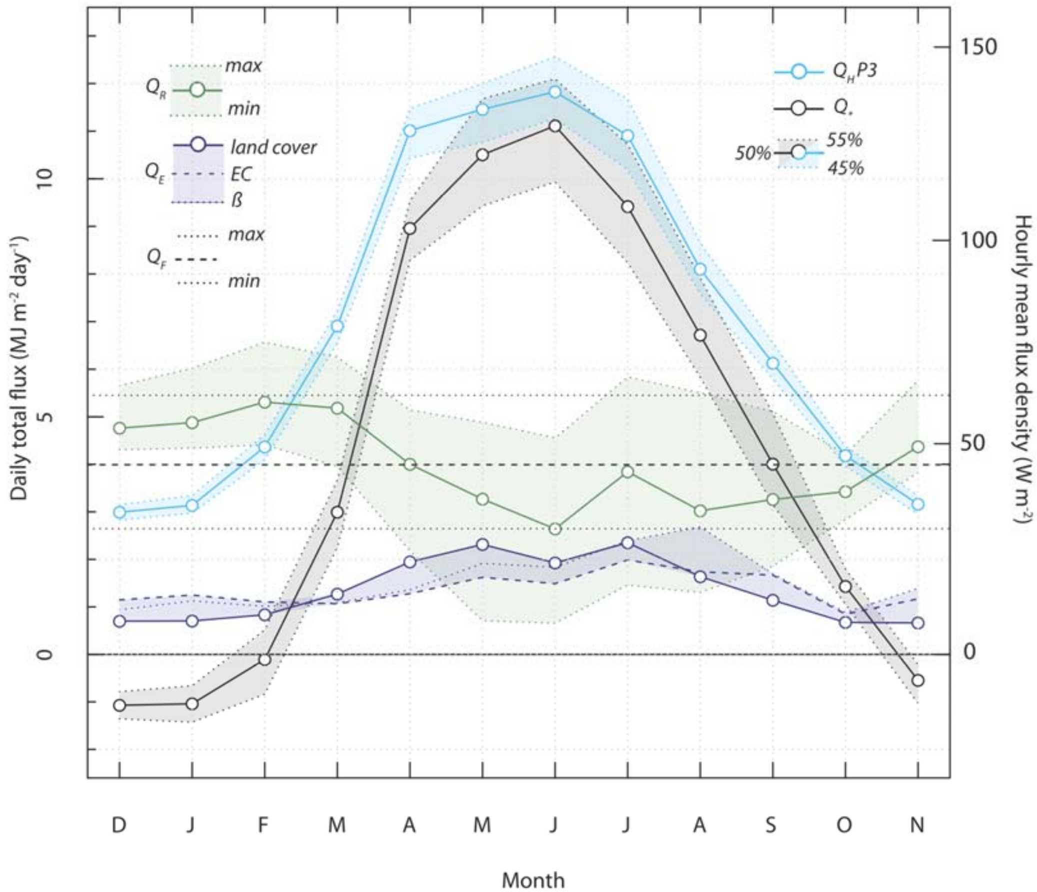
Crawford et al. 2017 QJRMS doi:10.1002/qj.2967

Normalized variations by surface wetness and surface cover



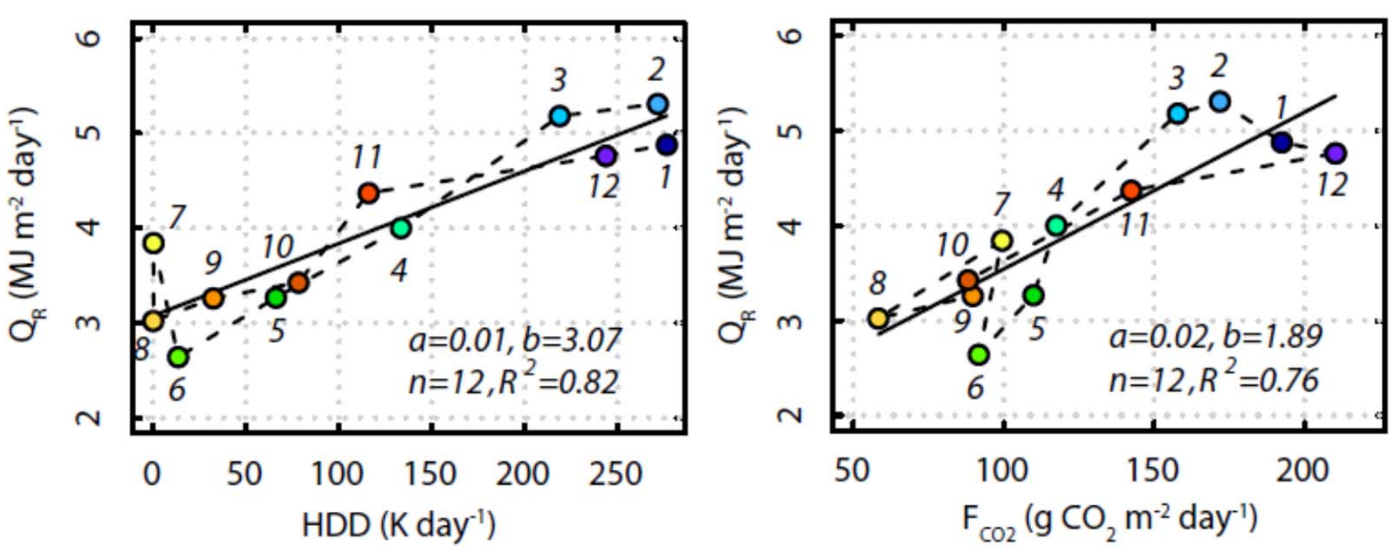
Crawford et al. 2017 QJRMS doi:10.1002/qj.2967

Monthly variability through the year



Crawford et al. 2017 QJRMS doi:10.1002/qj.2967

Monthly Residual ≈ Q_F Anthropogenic Heat Flux



$$Q_F \approx Q_R = Q* - (Q_H + Q_E)$$

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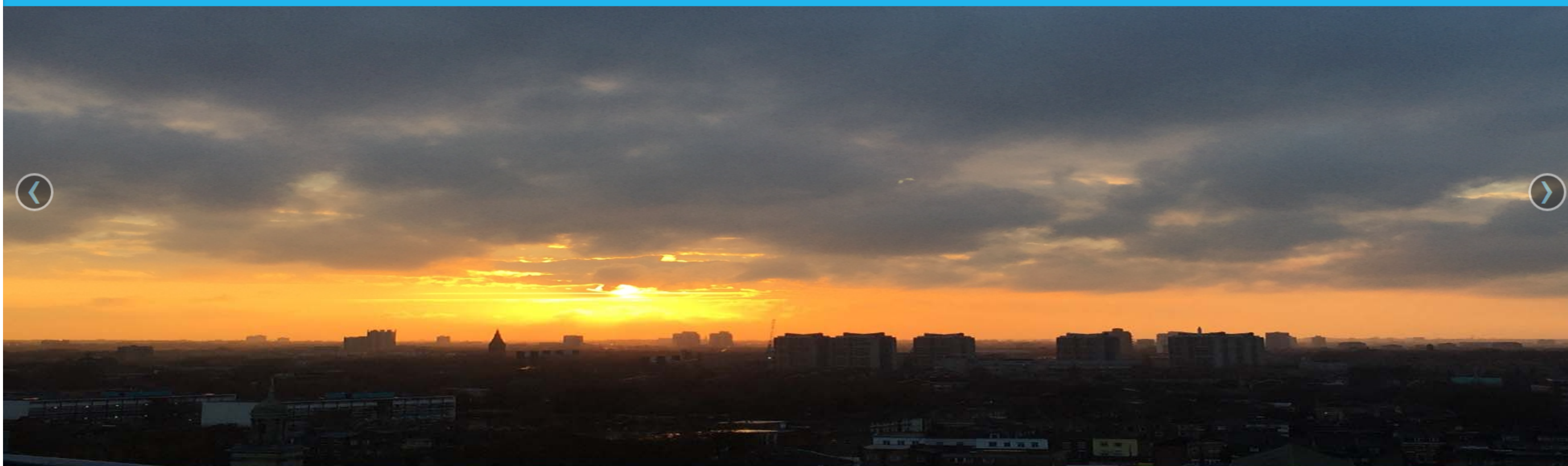
Crawford et al. 2017 ***QJRMS***, 143, 703, B, 817–833 *doi:10.1002/qj.2967*

www.urban-climate.net/content/

Urban Climate

Data and software tools

Home Data Data and Observation



Data

London Meteorological data (LUMA and Southwark).

Software tools

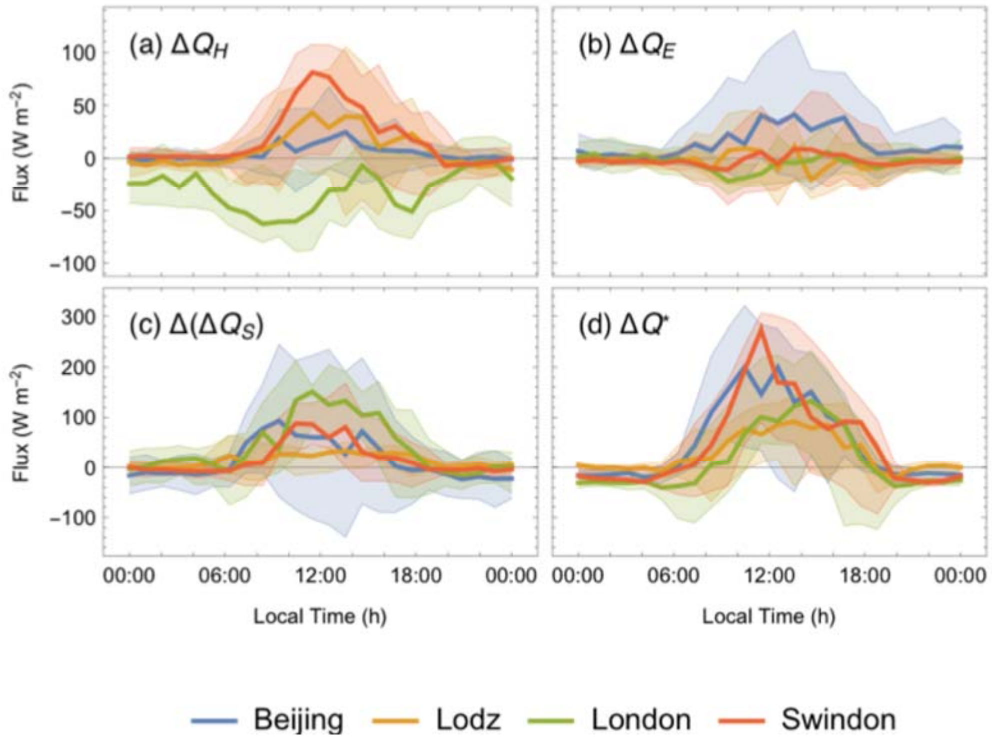
Information and download instructions for the UMEP, SUEWS and SOLWEIG models to analyse and predict urban micro-meteorological environmental conditions.

Our research

This page is maintained by the Urban micrometeorology research group at the University of Reading, UK.

Heat Wave-induced Changes in Urban Energy Balance

$$Q^* - \Delta Q_S = Q_H + Q_E$$



- Turbulent fluxes --> Inconsistent changes
- Storage heat fluxes → Overall increase
- Net all-wave radiation → Overall increase

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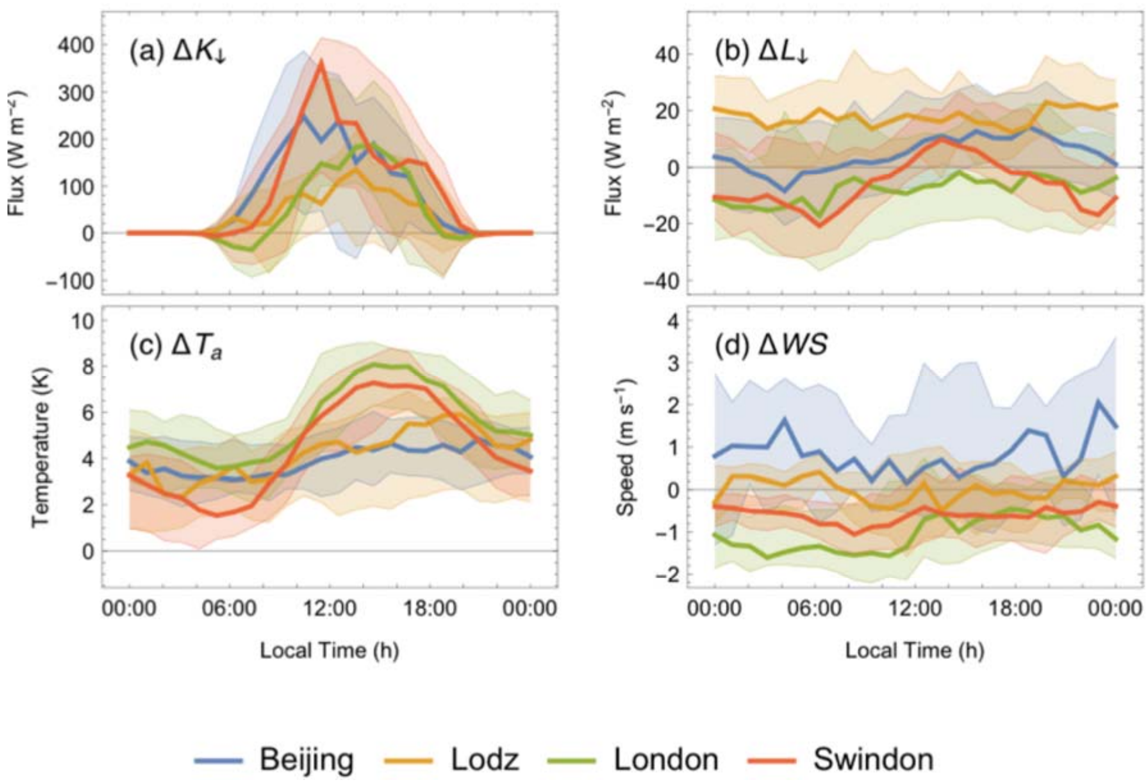
Sun et al. (2017) ERL doi:10.1088/1748-9326/aa922a

Heat Wave-induced Changes in Atmospheric Forcing Conditions



- Incoming solar radiation
  - Consistent increase
- Incoming longwave radiation
  - Inconsistent changes
- Air temperature
  - Consistent increases
- Wind speed
  - Distinct changes across cities

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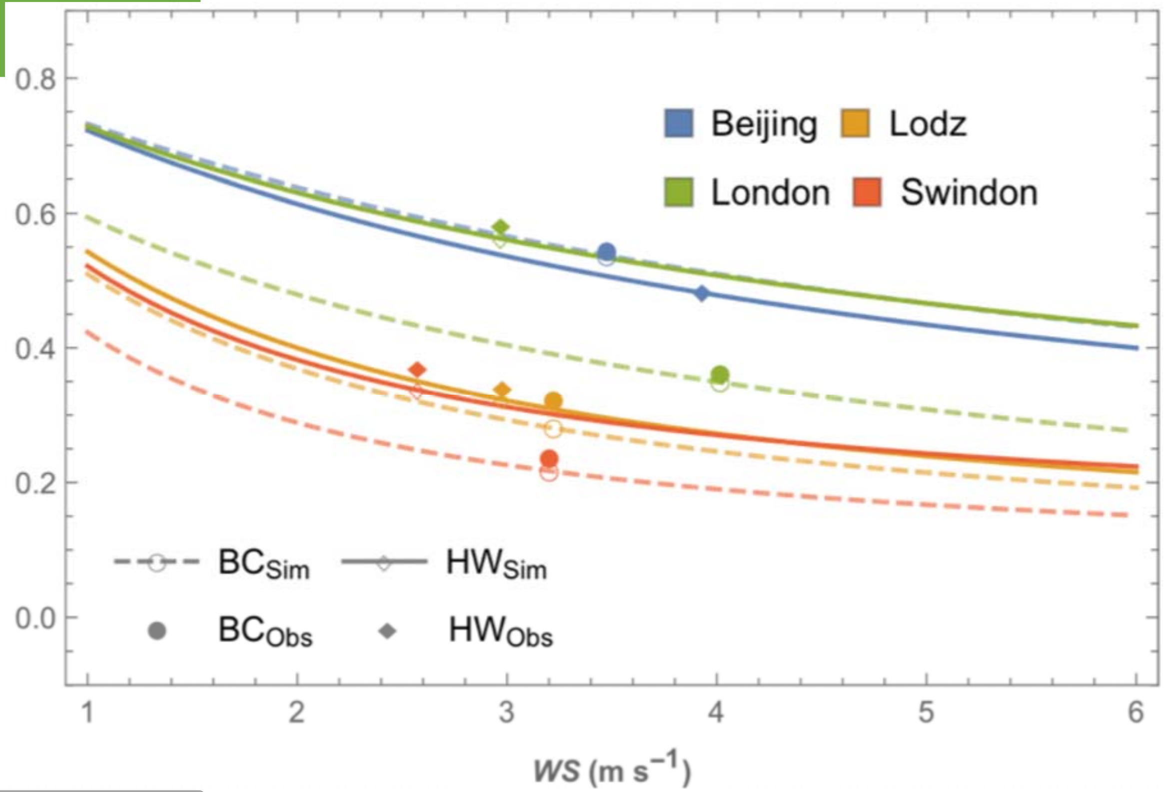
Sun et al. (2017) ERL doi:10.1088/1748-9326/aa922a

Impacts of Wind Speed on Heat Storage Ratio: AnOHM simulations

- Good agreement: observations & AnOHM simulations
  - HW- heat wave BC – before HW conditions
- Higher wind speed leads to decreased rQ_S
  - Enhanced turbulent transport
  - Decreased surface temperature

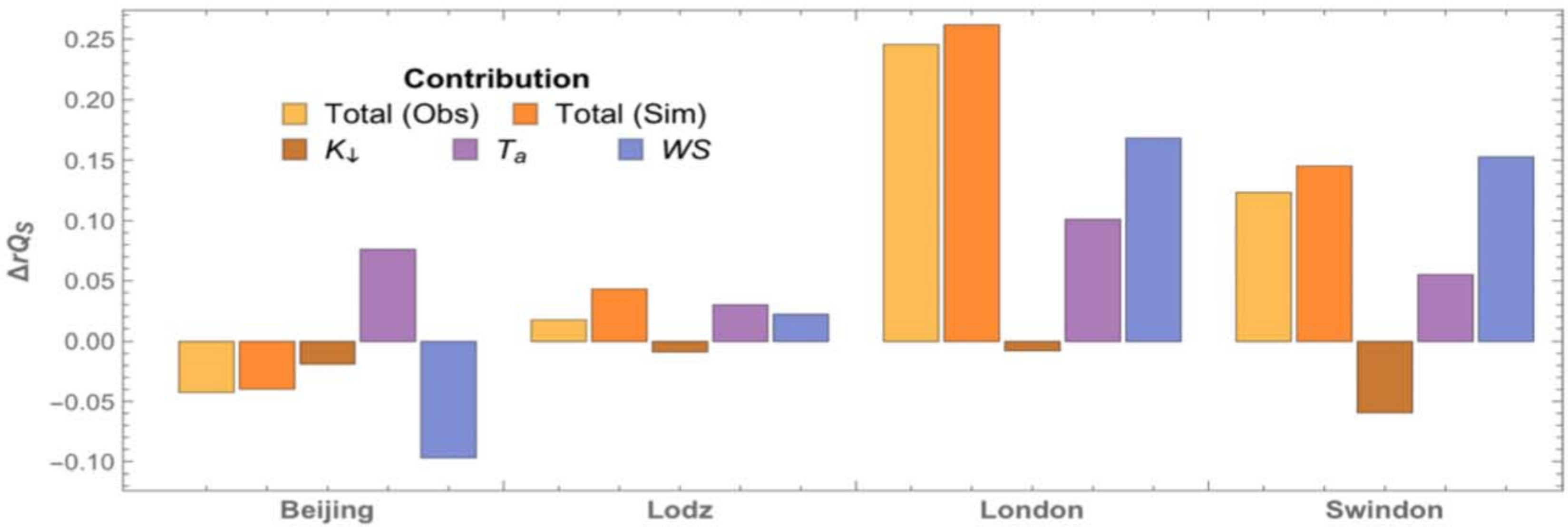
$$rQ_s = \frac{\Delta Q_s}{Q*}$$



Sun et al. (2017) ERL doi:10.1088/1748-9326/aa922a

Attribution of Heat Storage Ratio

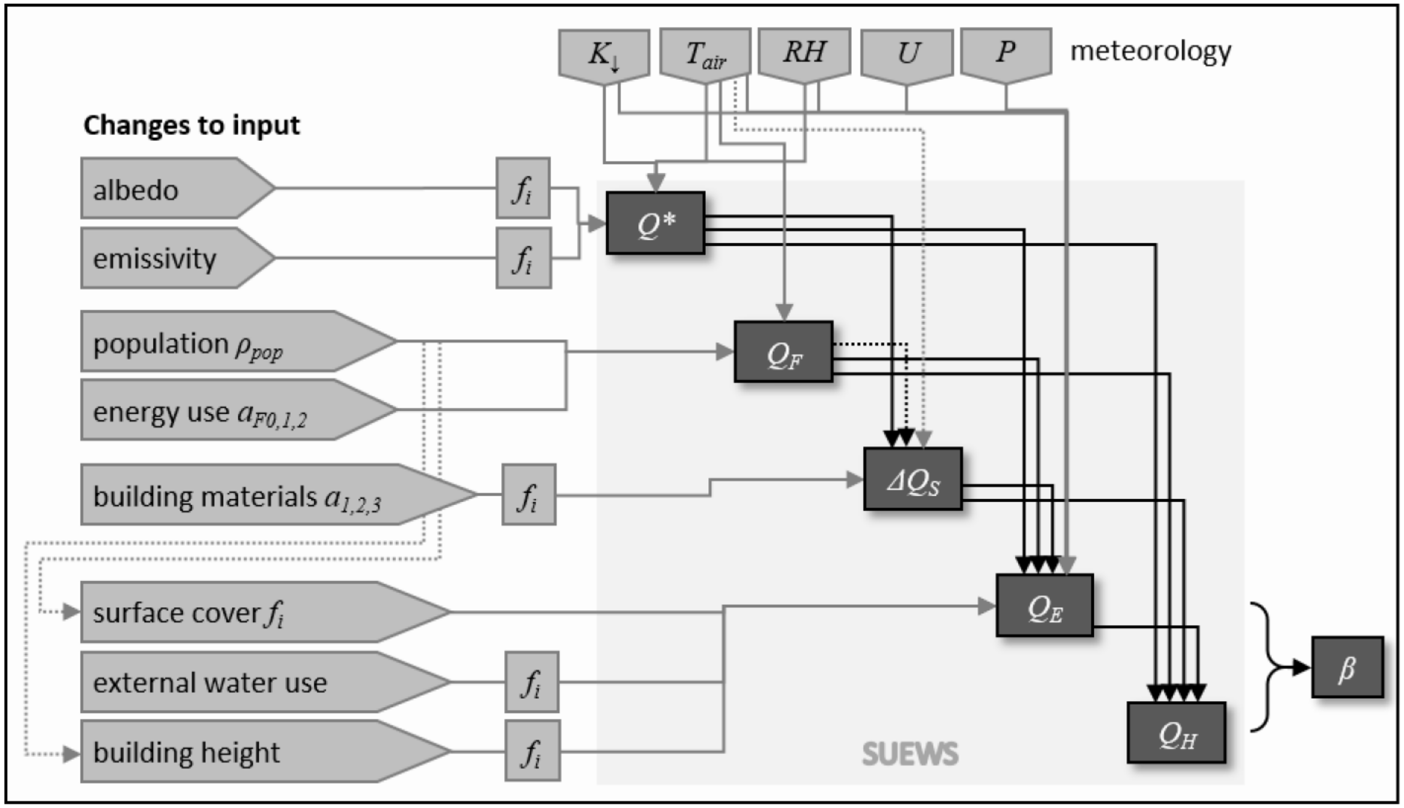
$$\Delta rQ_S \approx \frac{\partial rQ_S}{\partial K_\downarrow}\Delta K_\downarrow + \frac{\partial rQ_S}{\partial T_a}\Delta T_a + \frac{\partial rQ_S}{\partial WS}\Delta WS.$$



Wind speed: key determinant of heat wave-induced changes in storage heat

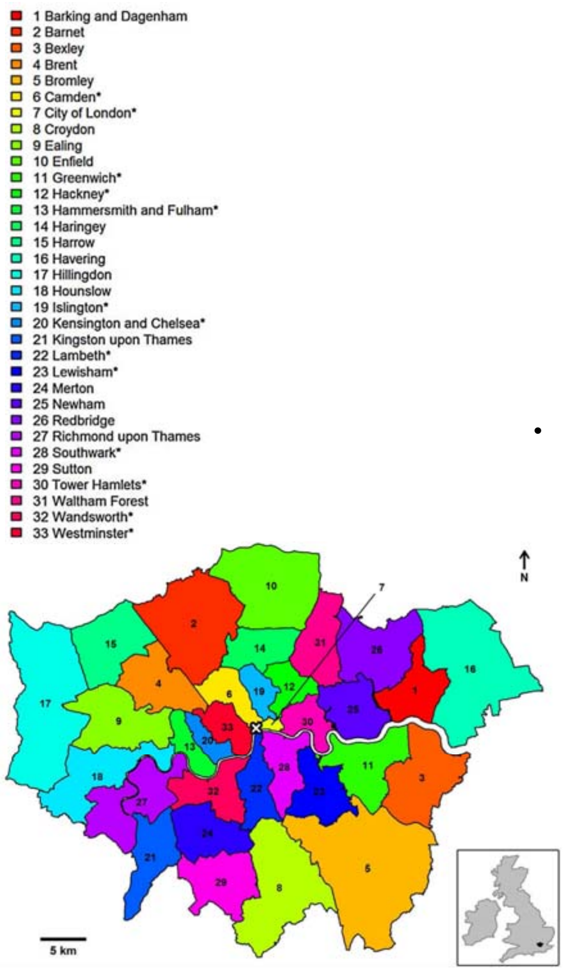
Sun et al. (2017) ERL doi:10.1088/1748-9326/aa922a

To provide solutions need to link surface properties to processes

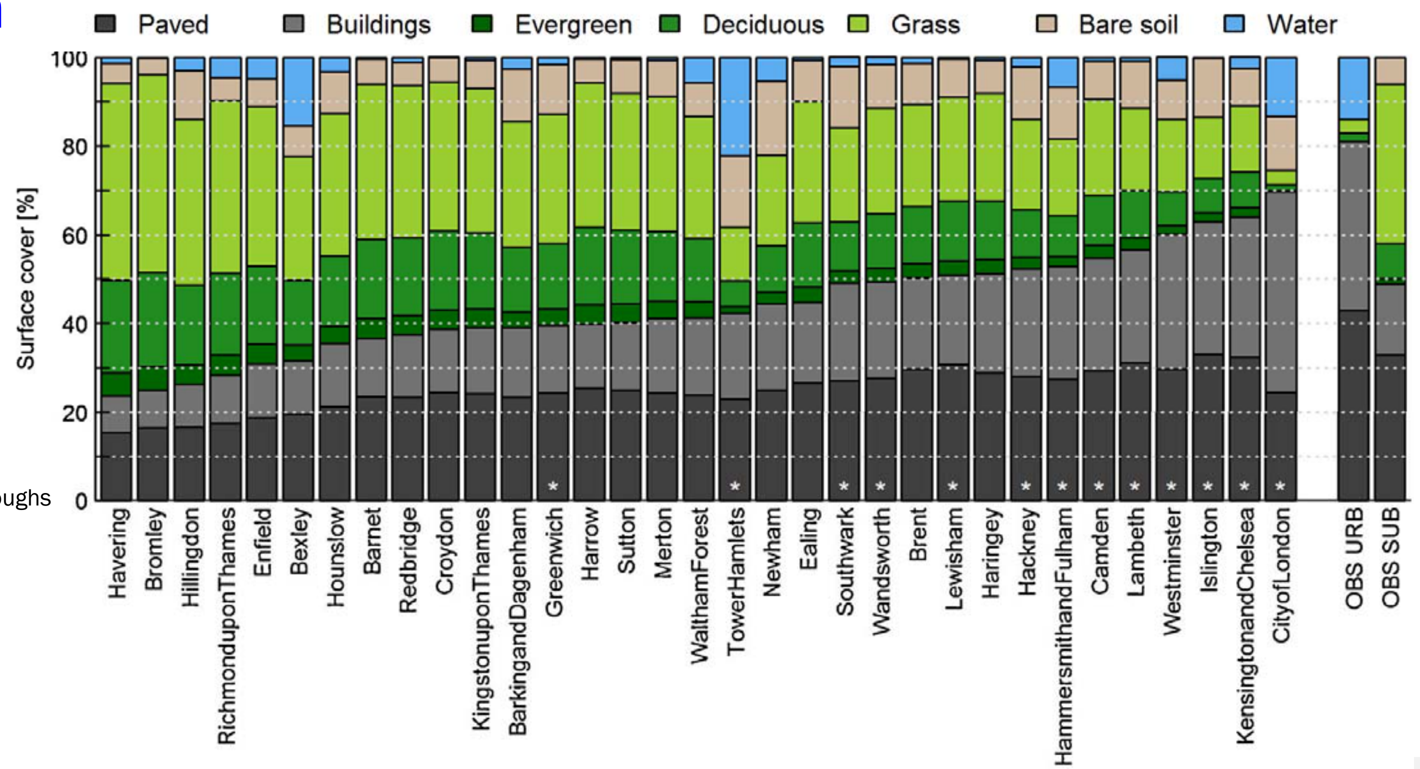


Ward & Grimmond 2017: *Landscape and Urban Planning*

Surface cover by borough



- Inner boroughs

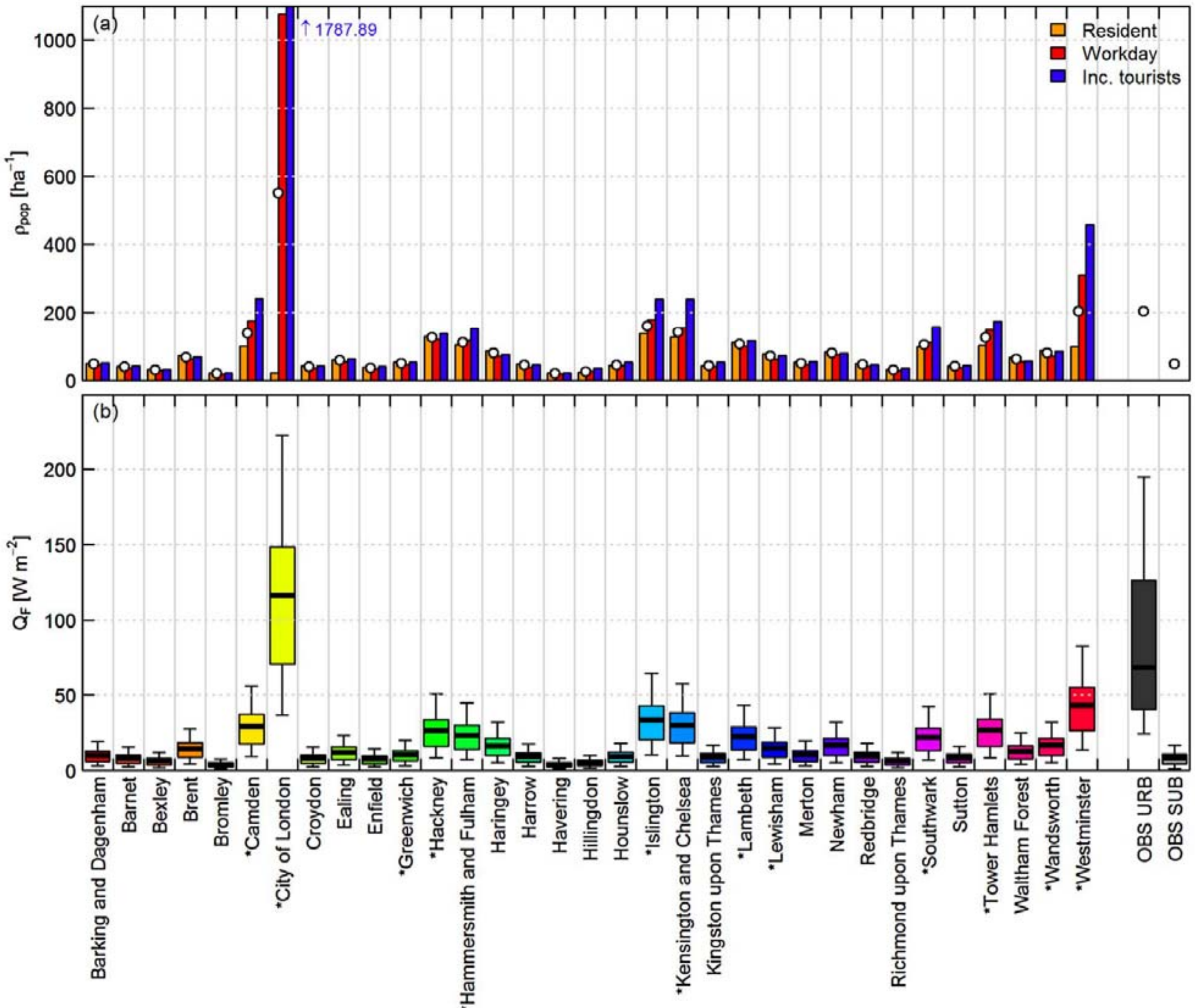


Havering
24% built
70% veg

Increasing built fraction (Paved + Buildings)

City of London
70% built
5% veg

Ward and Grimmond 2017 LUP



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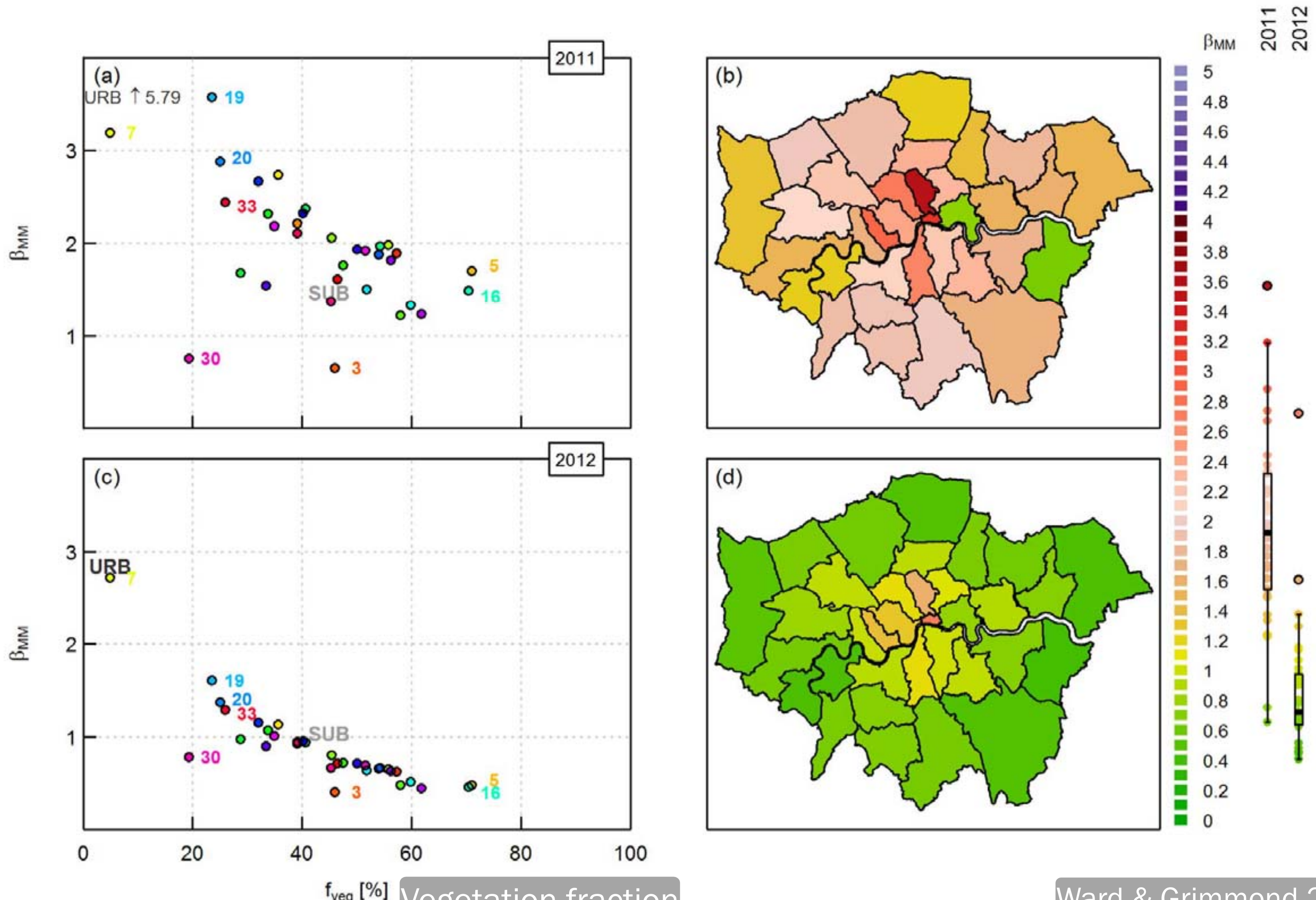
July: SUEWS model and observations (URB: KCL; SUB: Swindon)

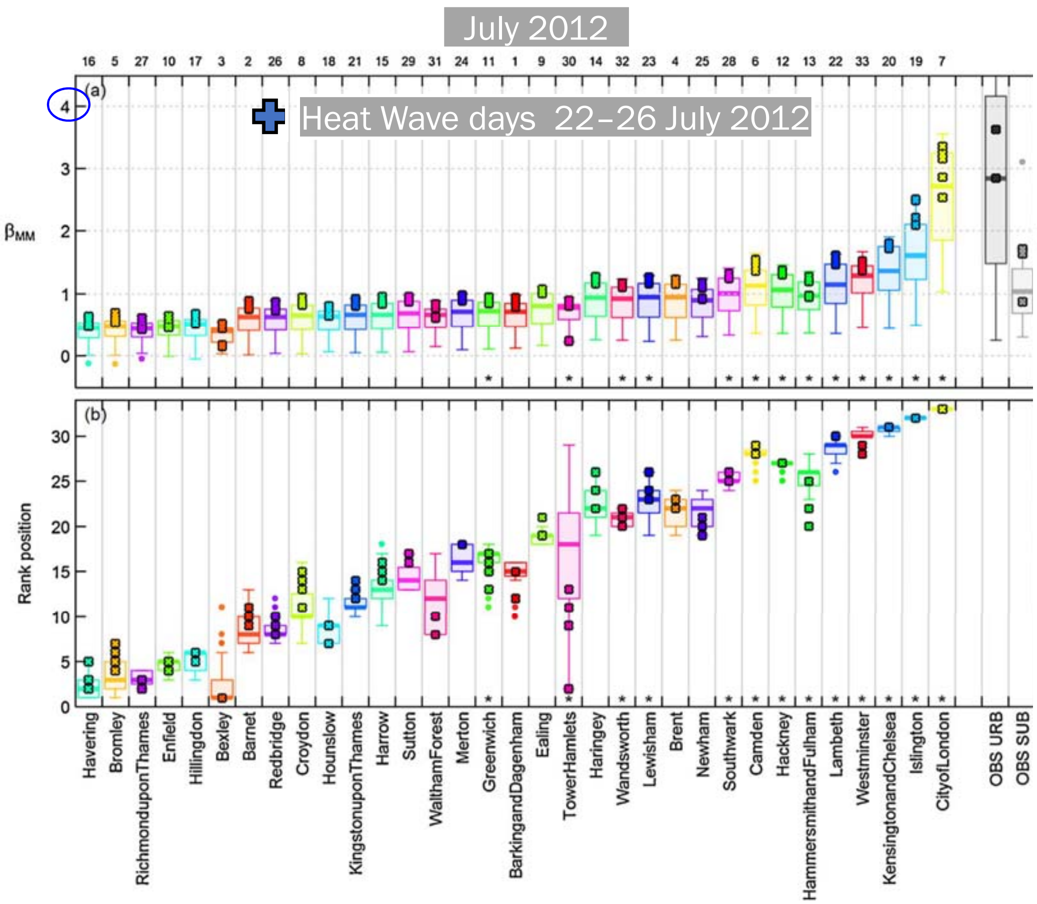
Median midday Bowen ratio β_{MM}

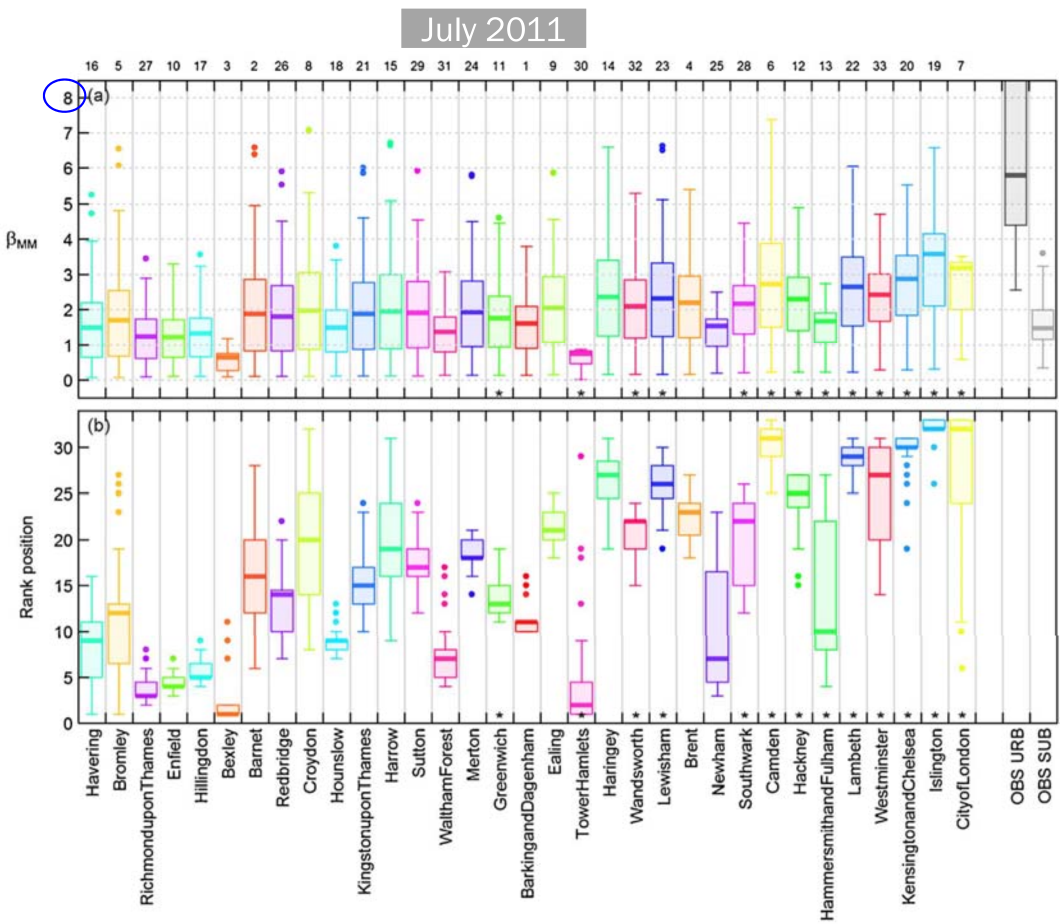


Vegetation fraction

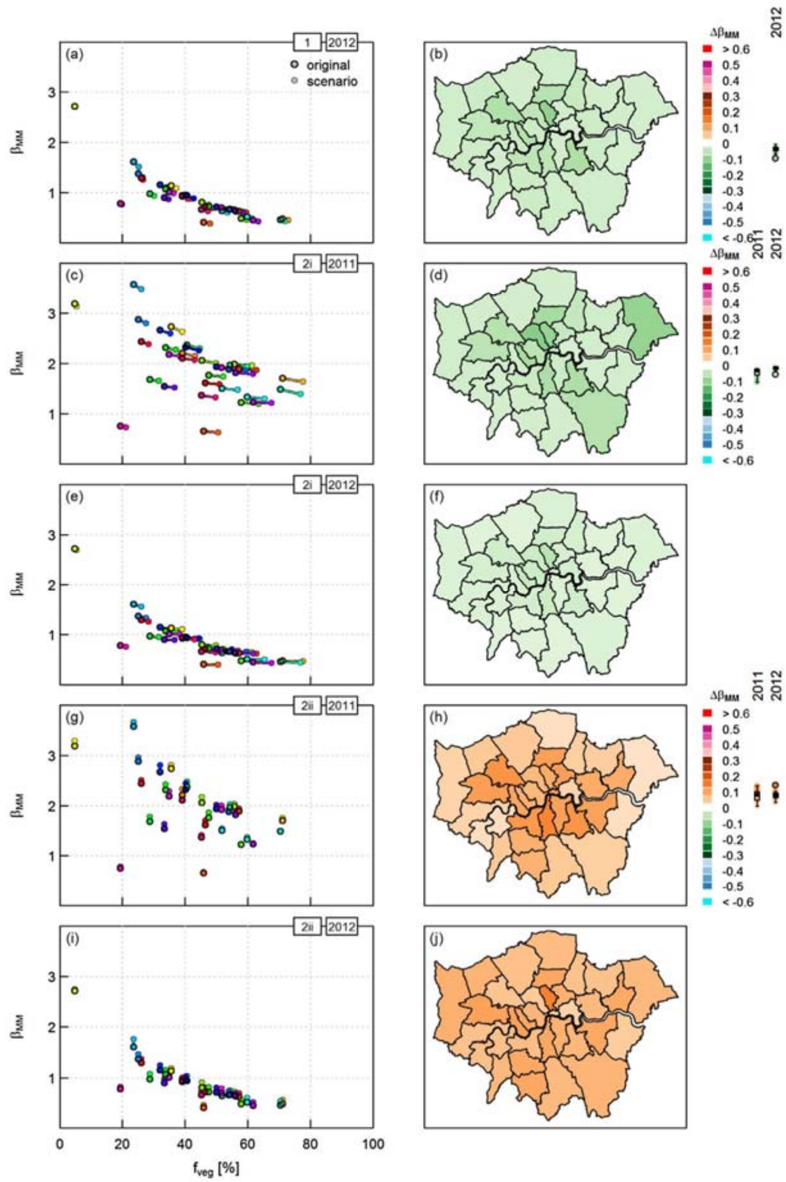
Ward & Grimmond 2017: *LUP*

Median midday Bowen ratio β_{MM}





Ward & Grimmond 2017: *LUP*



Scenario 1

Δ **surface cover** equivalent to returning today's garden composition to that of 1998–9

Scenario 2i - Increase tree cover by +25%

Replacing paved surfaces

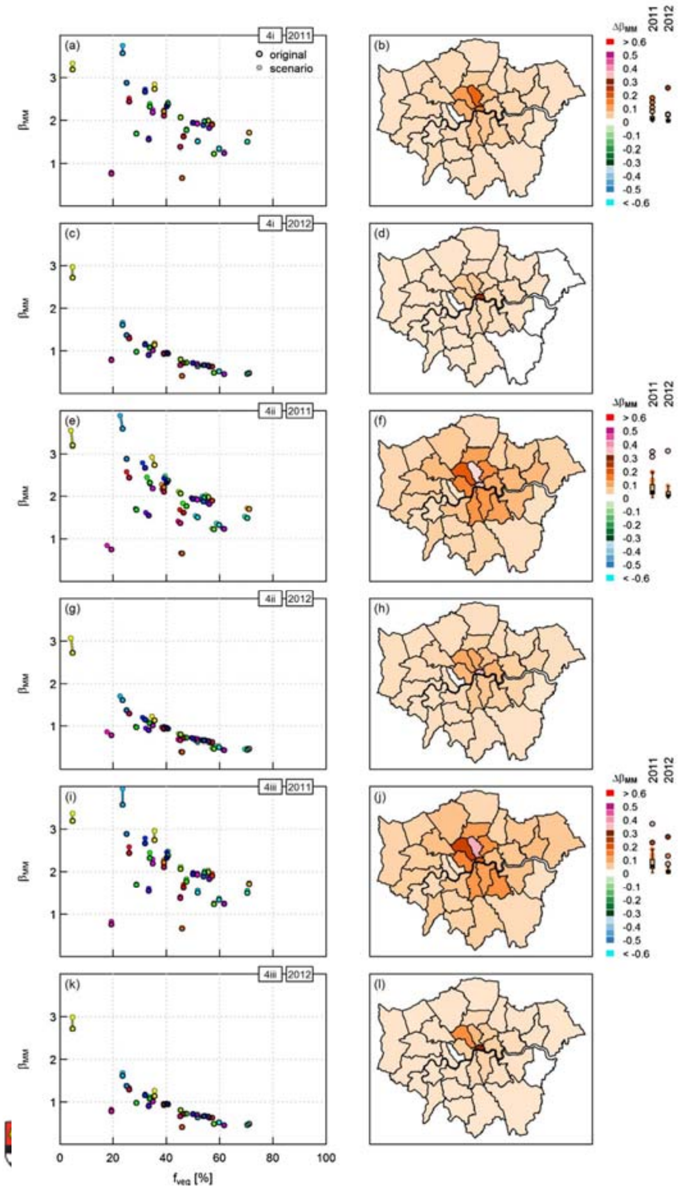
2011

2012

Senario 2ii

- Replacing grass surfaces
- 2011

- 2012



Increase in population to 2020 Projection

4i: no additional building

2011

2012

4ii: increase building fraction, buildings replace bare soil & vegetation

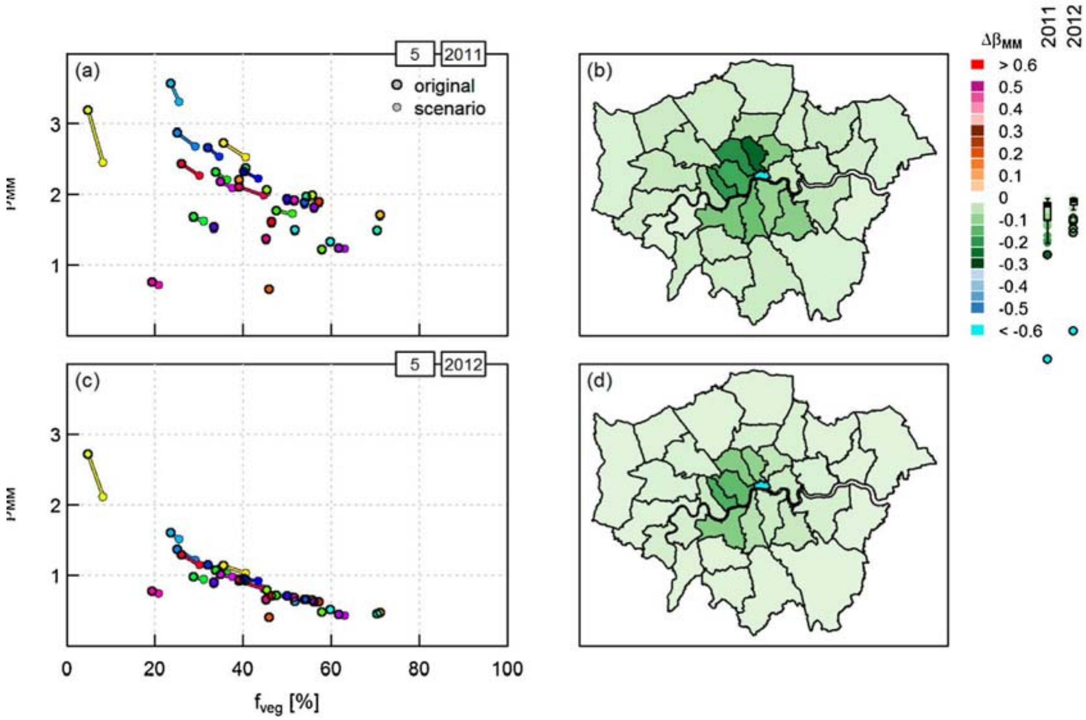
2011

2012

4iii increase in building fraction, buildings replace bare soil only

2011

2012



Scenario 5: **Climate-sensitive adaptation**

- Q_F Coefficient a_{F0} and a_{F2} adjusted to reflect ↓ 20% building energy use
- Coefficient a_{F0} adjusted to reflect reduced ↓ 10% vehicle energy use
- Tree cover ↑ 25% - reduction in paved surfaces for inner boroughs
- 25% of bare soil surfaces changed to grass for wealthy boroughs

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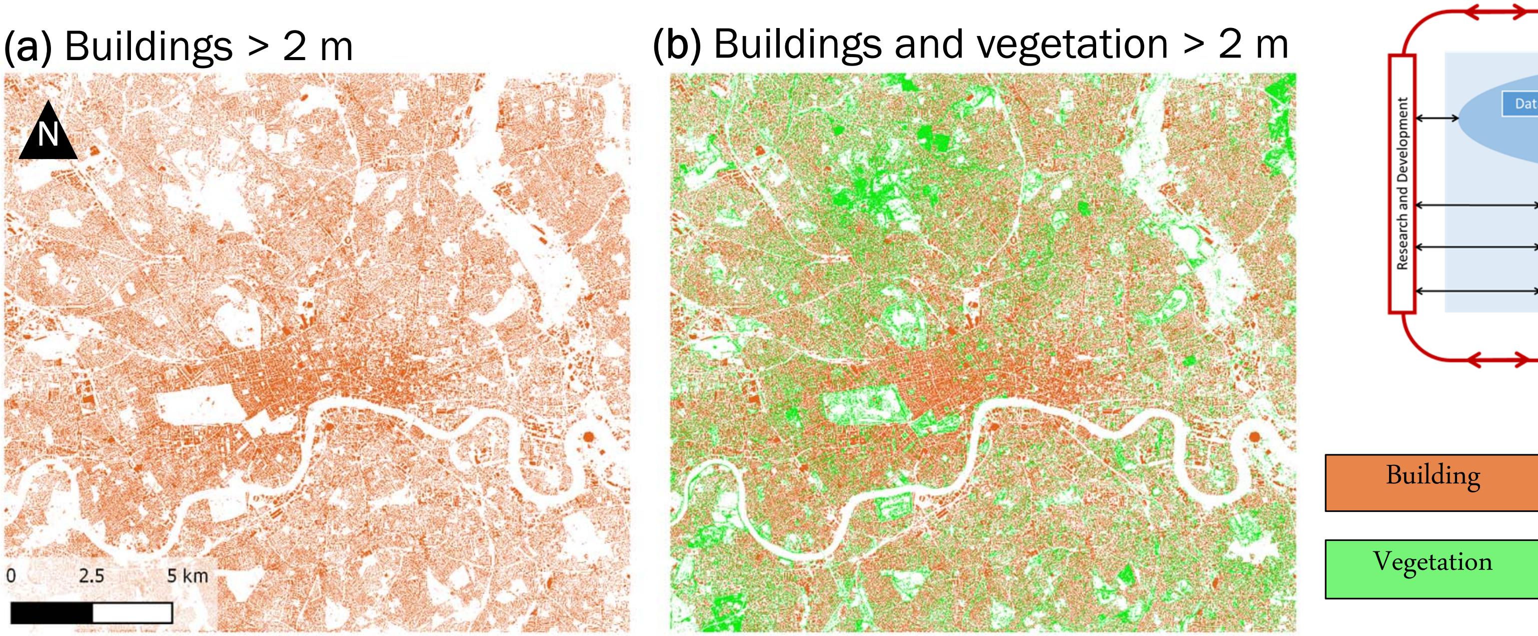
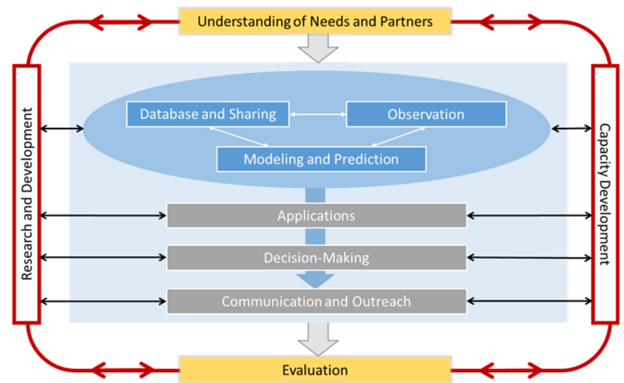
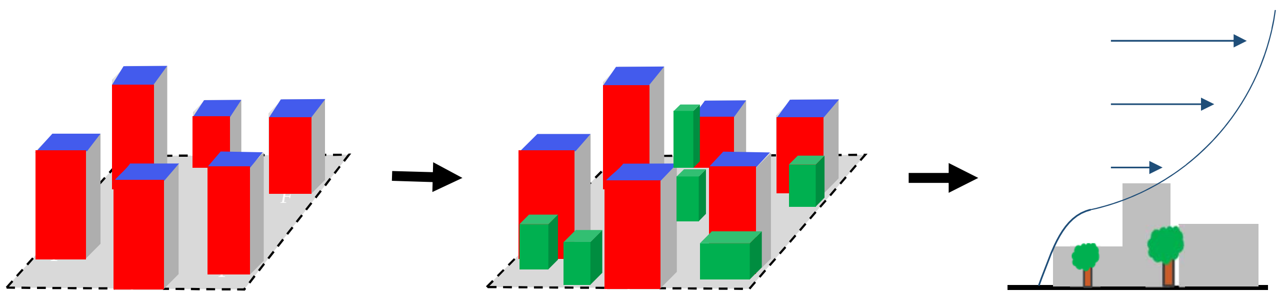
Model parameters also need to account for both buildings and vegetation

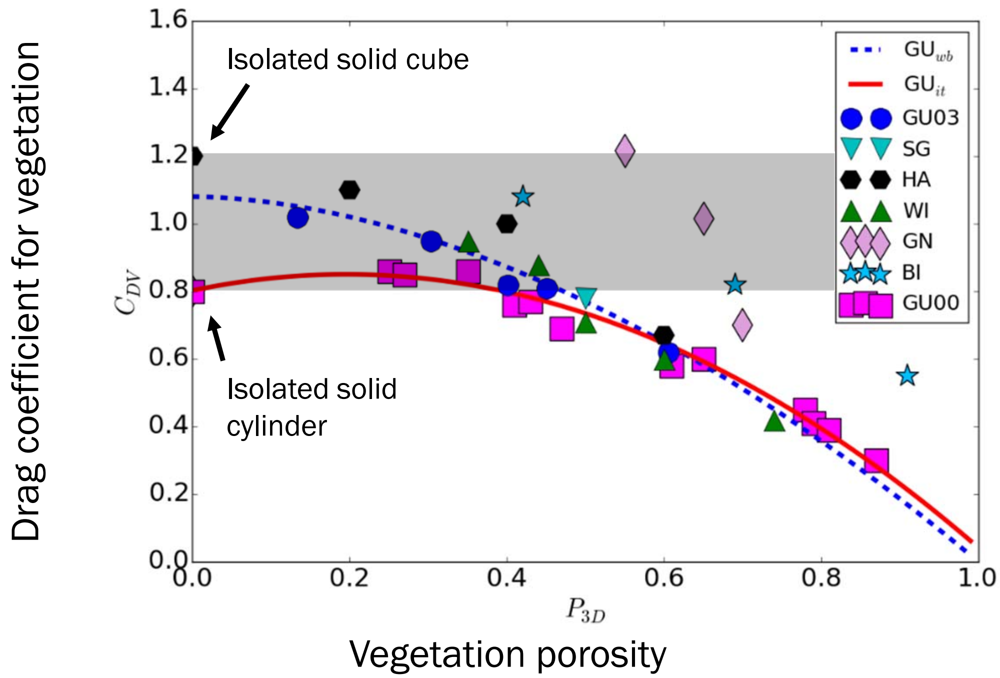






Morphometric method development

- Inclusion of vegetation (Kent et al. 2017c):
  - Height properties of all roughness elements
  - Porosity corrected plan area
  - Drag formulation: variation of vegetation drag with porosity…



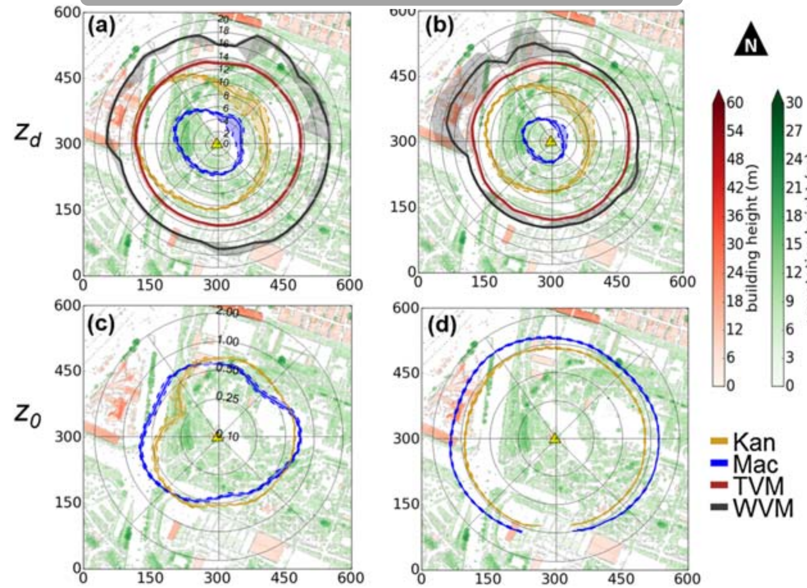
Kent et al. 2017: Aerodynamic roughness parameters in cities: inclusion of vegetation. JWEIA 169: 168-176 10.1016/j.jweia.2017.07.016

Vegetation: impacts parameters

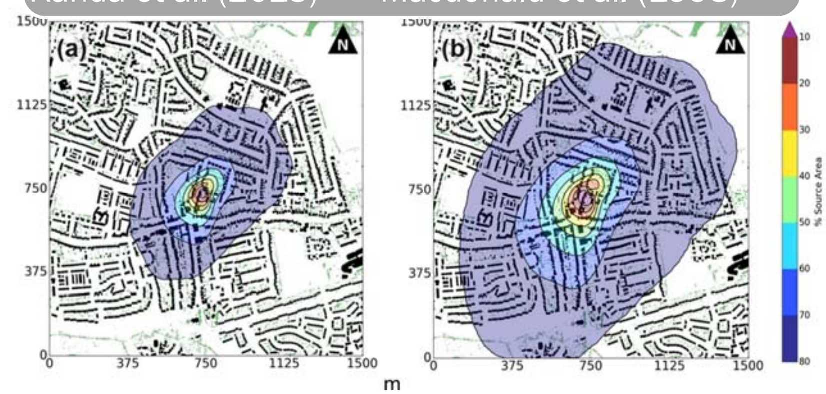
- Obvious signal of vegetation (z_d, z_0, $\overline{U}_z$)
- Directional variability and seasonal signal
- Improved wind speed estimation

Seoul Forest Park Swindon

Leaf-on Leaf-off



Source area model: Kormann and Meixner (2001)
Swindon JJA 2011 & 2012.
Kanda et al. (2013) Macdonald et al. (1998)



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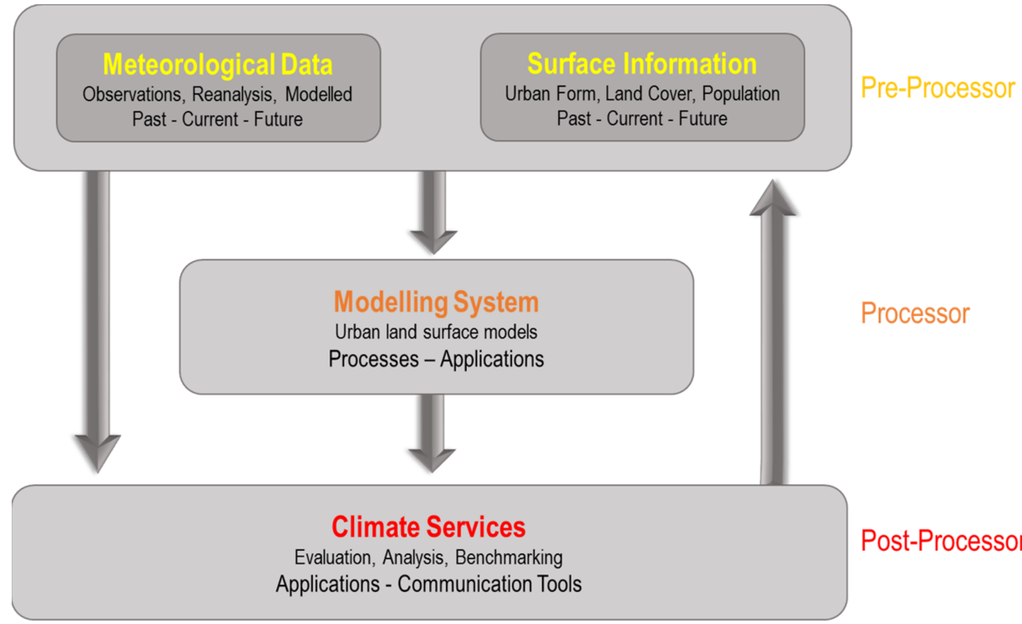
Kent et al. 2018 **Urban Ecosystems** [10.1007/s11252-017-0710-1](10.1007/s11252-017-0710-1)

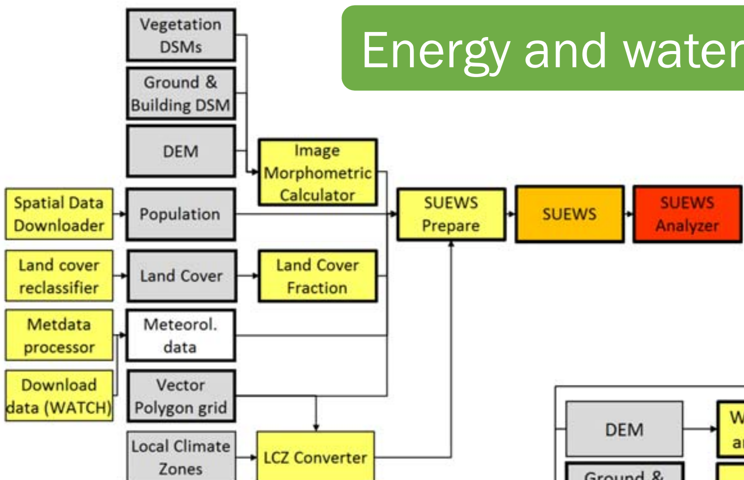
City Based Climate Service Tool

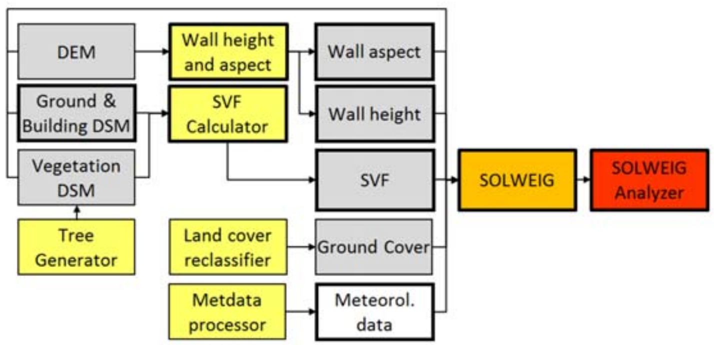
UMEP – *Urban Multi-scale Environmental Predictor*

- Open source /Free software
  - http://urban-climate.net/umep/UMEP_Manual
  - http://urban-climate.net/umep/SUEWS



Energy and water exchanges





Thermal stress

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Final Comments

- To help the wide range of decision makers keep our cities operational we need to work together as an integrated community
- National and international recognition of this (e.g. WMO Guide being developed)
  - Various communities need to contribute this
  - Along the way new research questions will arise and continue the iteration

- UMEP
  - Allows us to combine tools in a framework that researchers and stakeholder partners can use
  - e.g. roughness parameters, WUDAPT, SUEWS, Q_F - LUCY (LQF), GQF, SUEWS (Gabey et al. 2018 TAC)
- Challenges
  - New instrumentation
  - To representing urban areas