# First Annual Anthony J. Brazel Urban Climate Lecture

## Urban meteorology & climate research: importance for integrated city services

Sue Grimmond

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*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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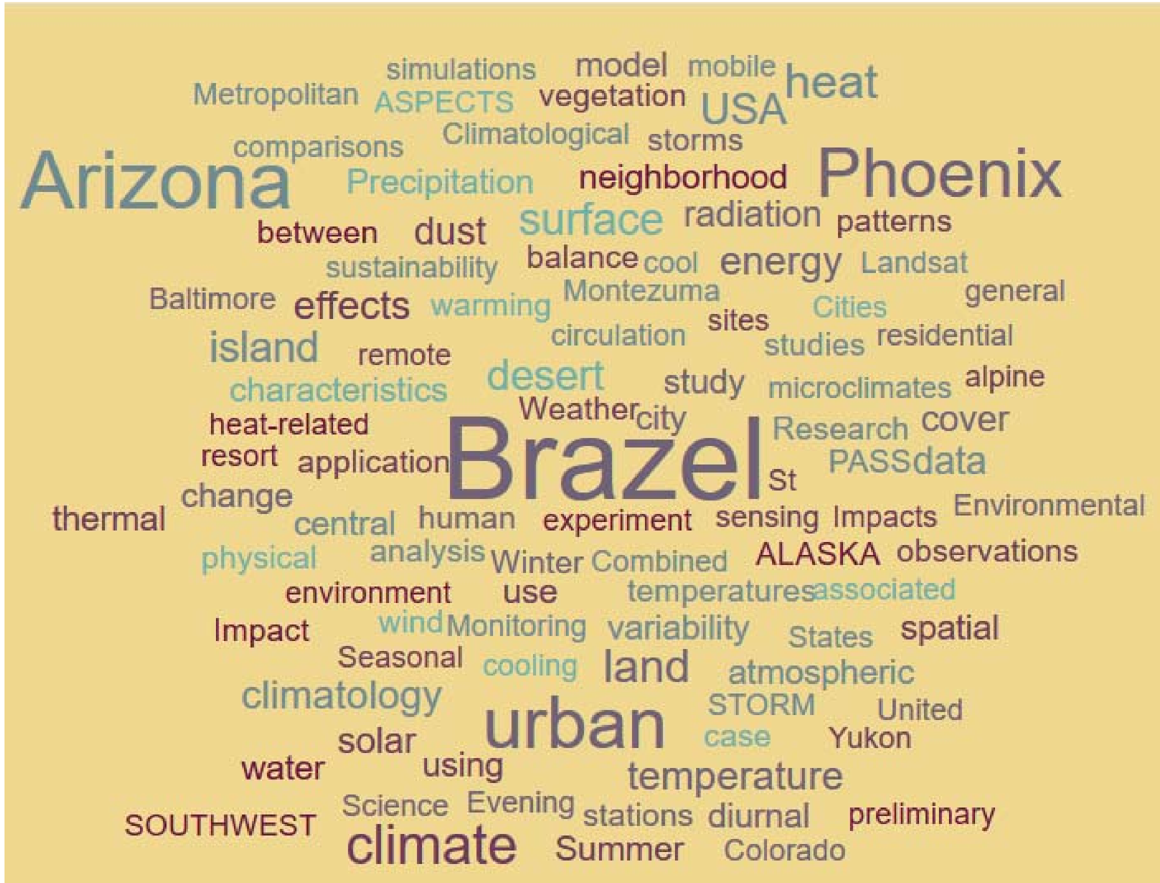
# Tony Brazel

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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)

*Battersea*

*Fort McMurray*

Greenwich, London

*Kolkata*

*Times Square, NYC, Storm Jonas*

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


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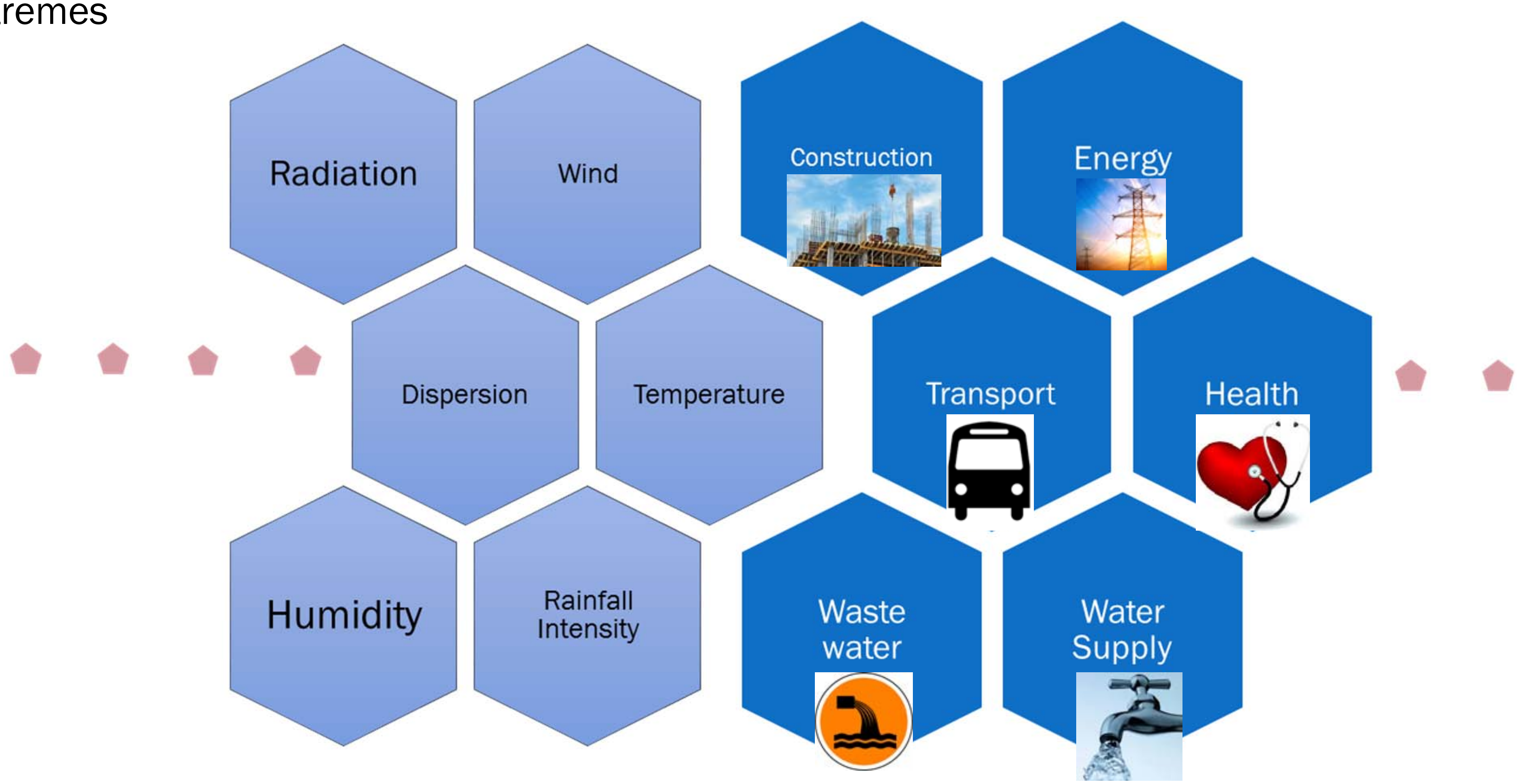
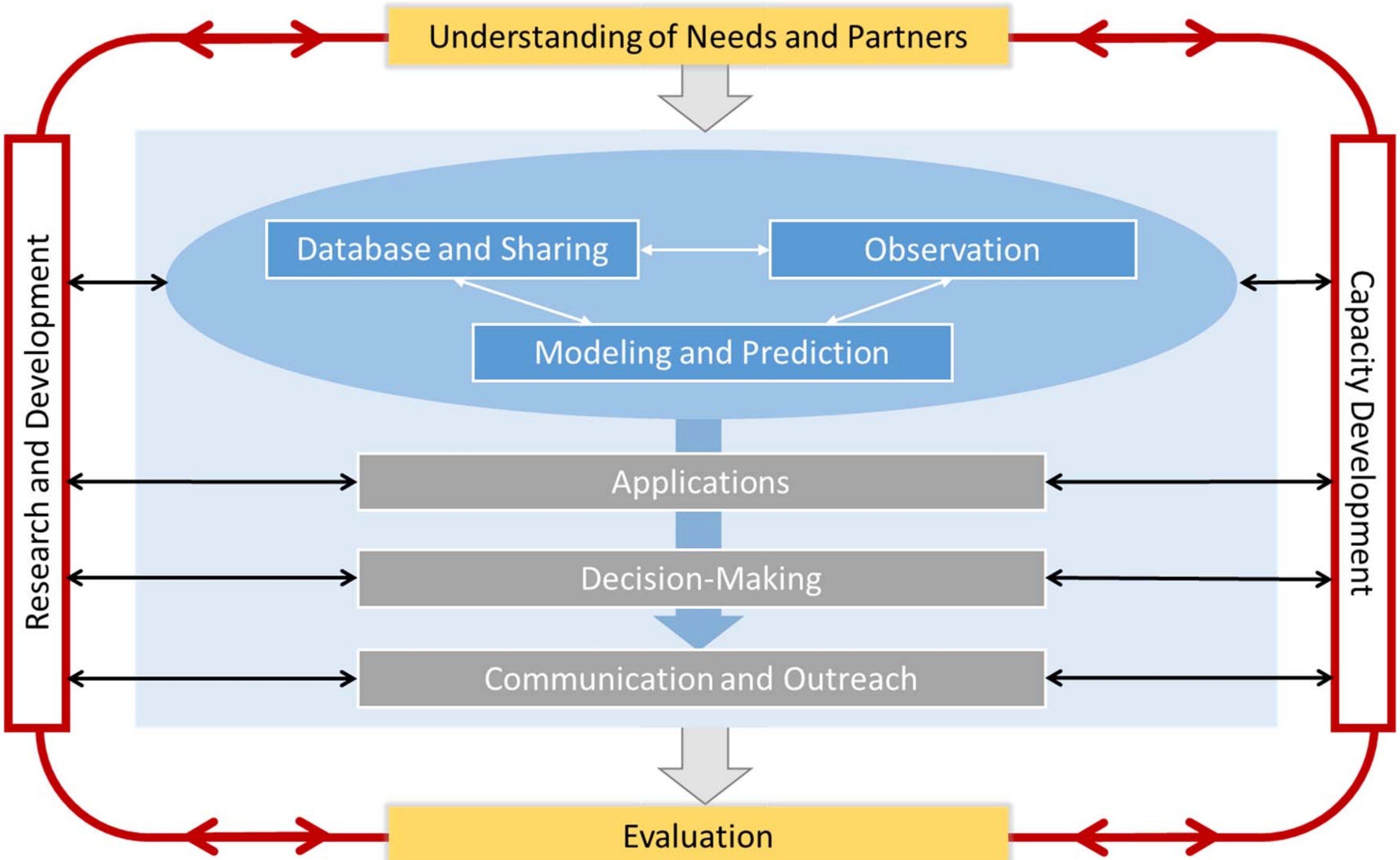
# Systems: interlinked

- Day-to-day operations
- Extremes

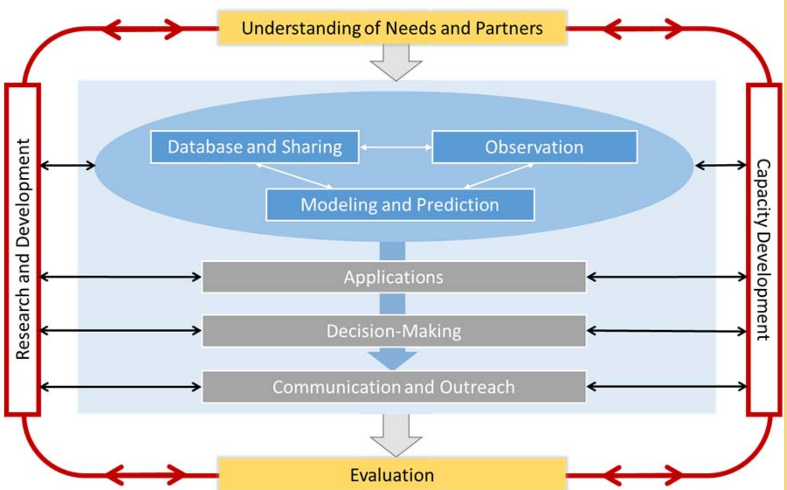


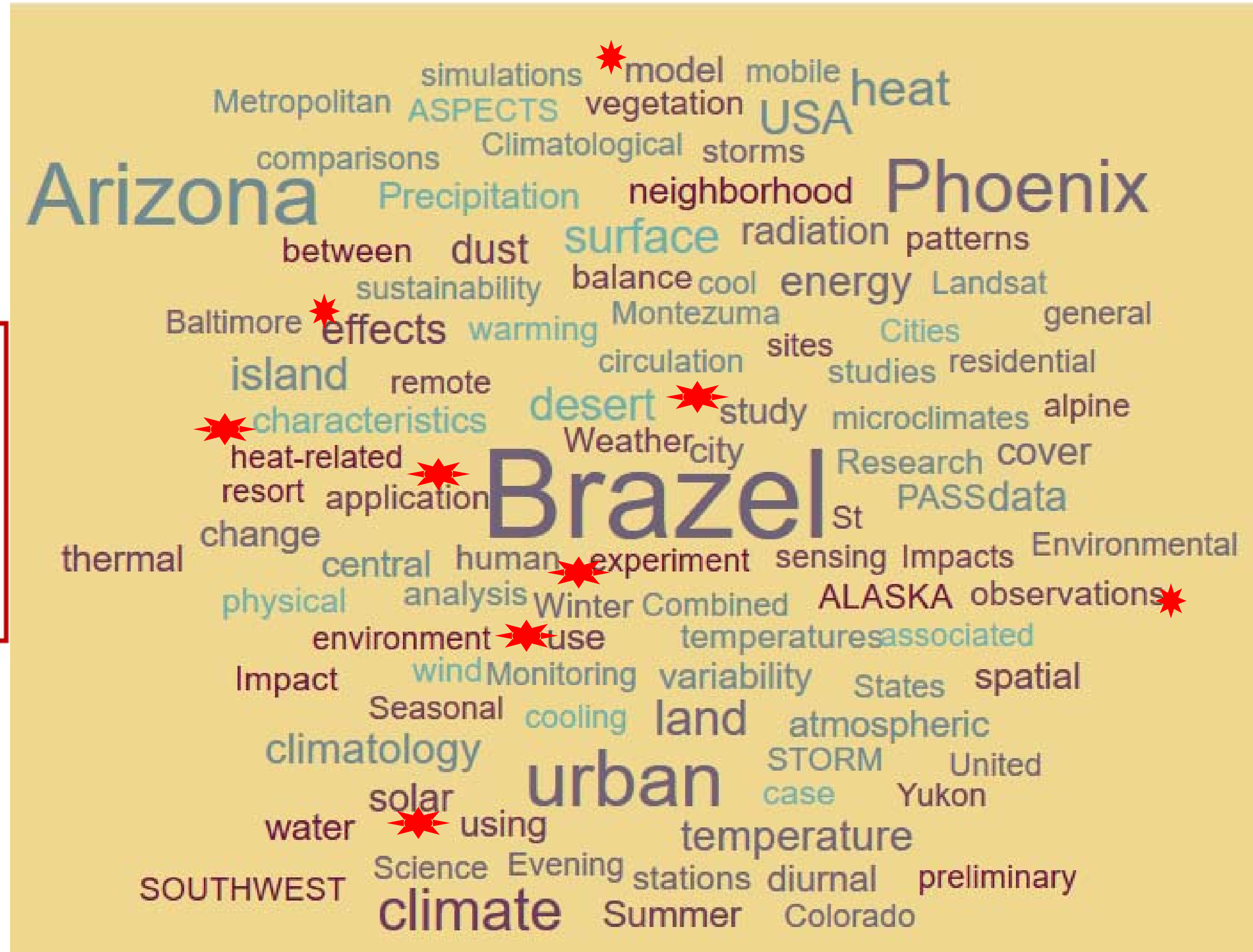
# Integrated Urban, Weather, Environment, Climate, Water and related Services




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

# Tony Brazel


Understanding of Needs and Partners
Research and Development
Database and Sharing
Observation
Modeling and Prediction
Capacity Development
Applications
Decision-Making
Communication and Outreach
Evaluation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temperature
Science
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stations
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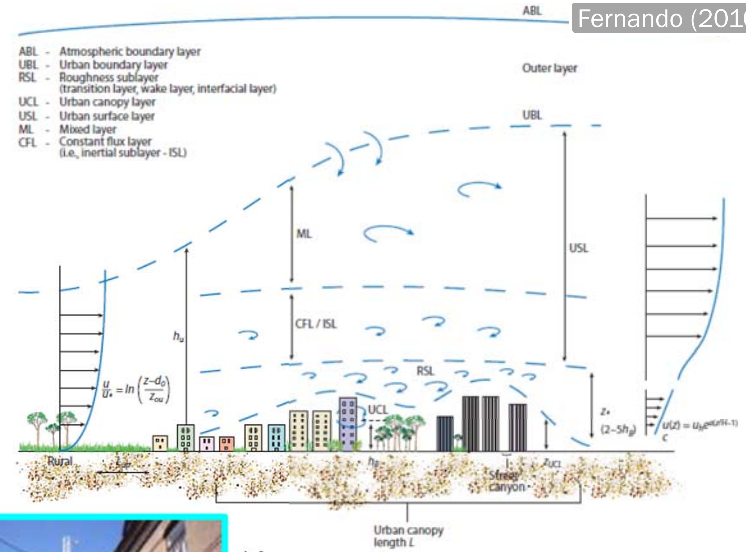
SOUTHWEST
climate
Summer
Colorado

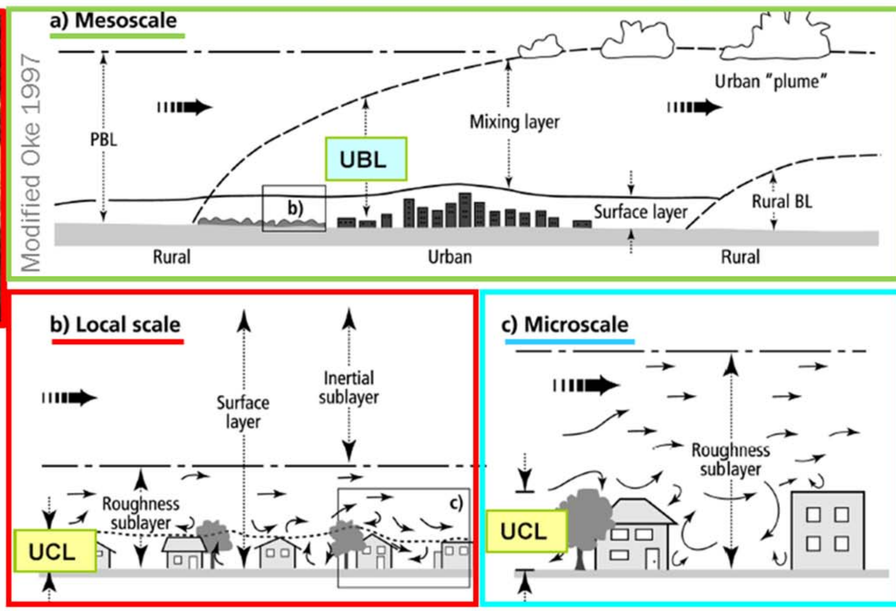
# Challenge of scale

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



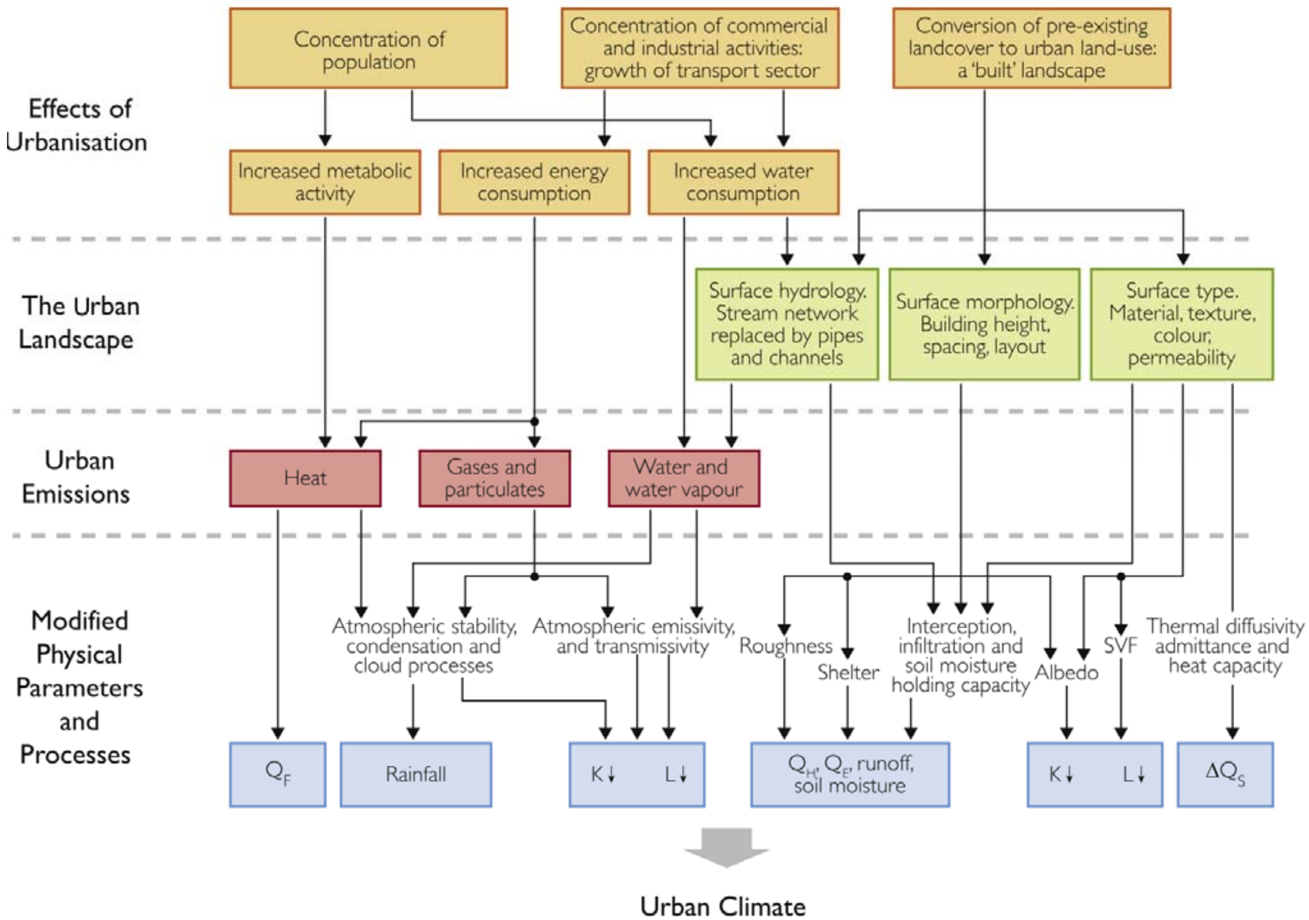








# Urban Atmospheric Processes




Cleugh and Grimmond (2012)

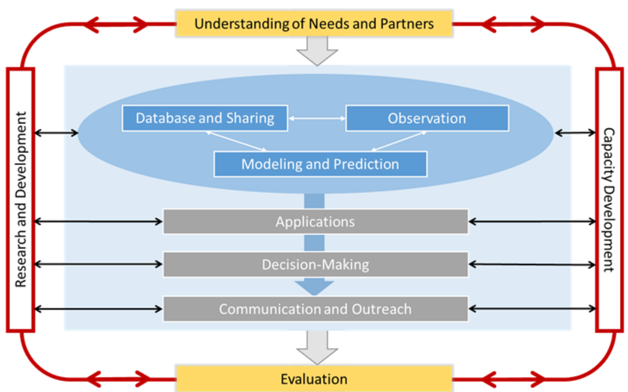
# Numerous constraints

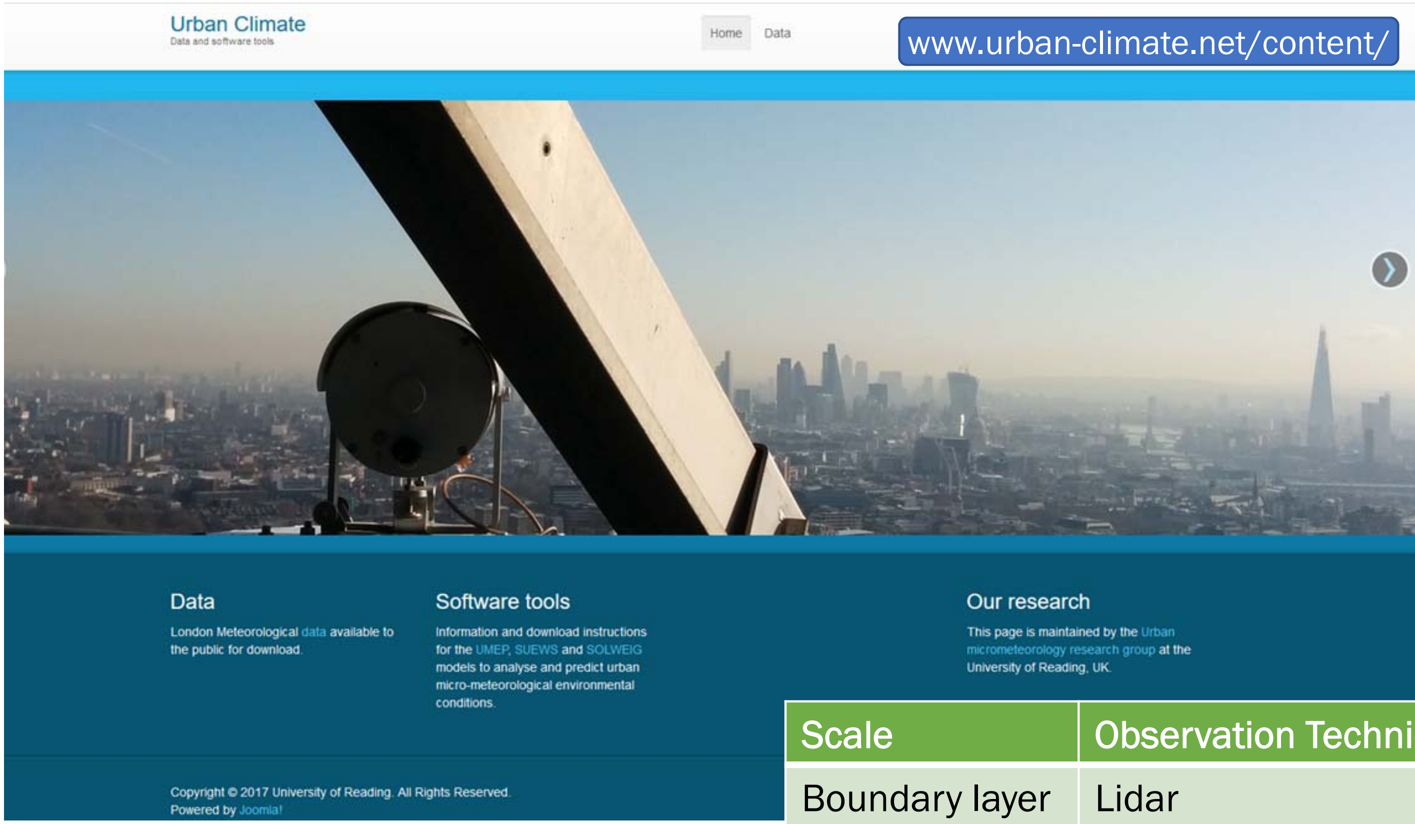
- MOST – breaks down close to the surface
- Urban roughness elements large
- Thermal remote sensing – coarse spatial scales or coarse temporal scales (+ need clear skies)
- Spatial heterogeneity
  - 3-d nature of the urban surface
- Anthropogenic effects
  - Behaviour change heat and mass exchanges

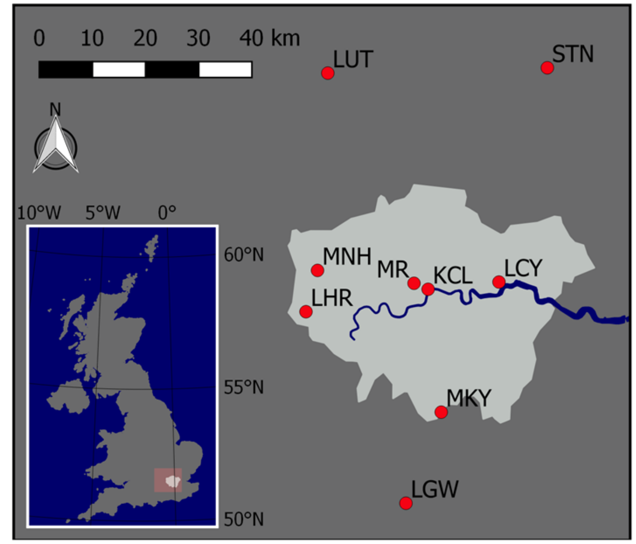
(Barlow et al. 2017 BAMS)

## Focus

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



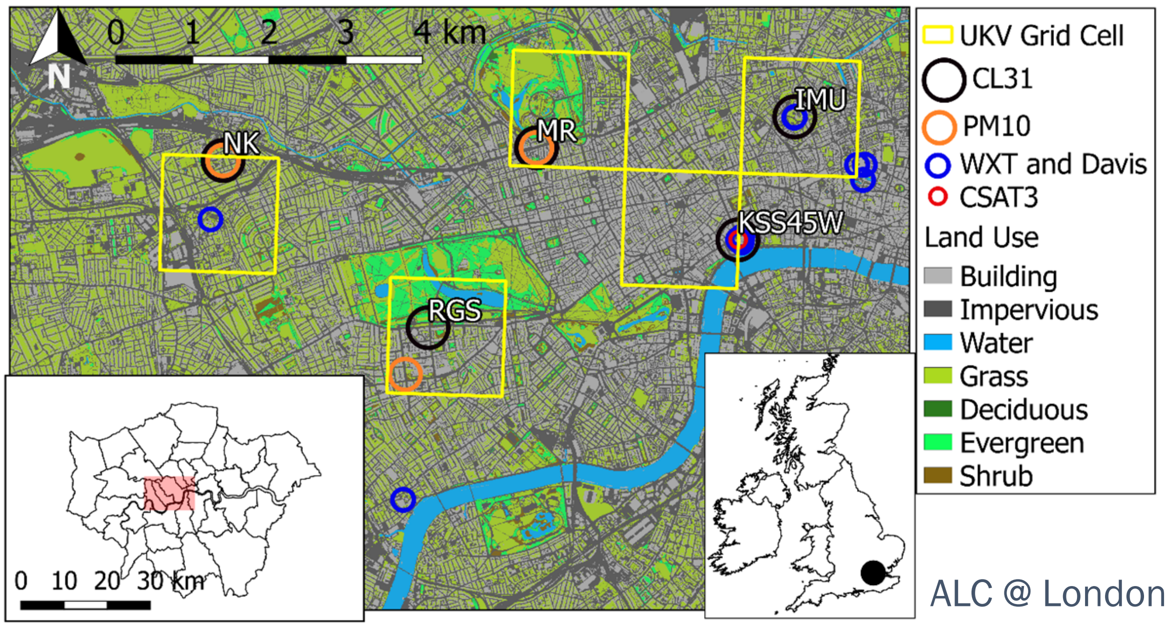



| Scale | Observation Technique | Modelling |
|---|---|---|
| Boundary layer | Lidar | aerFO |
| | | MLH |
| Neighbourhood | Scintillometry | |
| | EC (eddy covariance) | SUEWS |
| | | Roughness |
| Canyon | Thermal IRT | DART |

# Automatic lidar ceilometer (ALC)

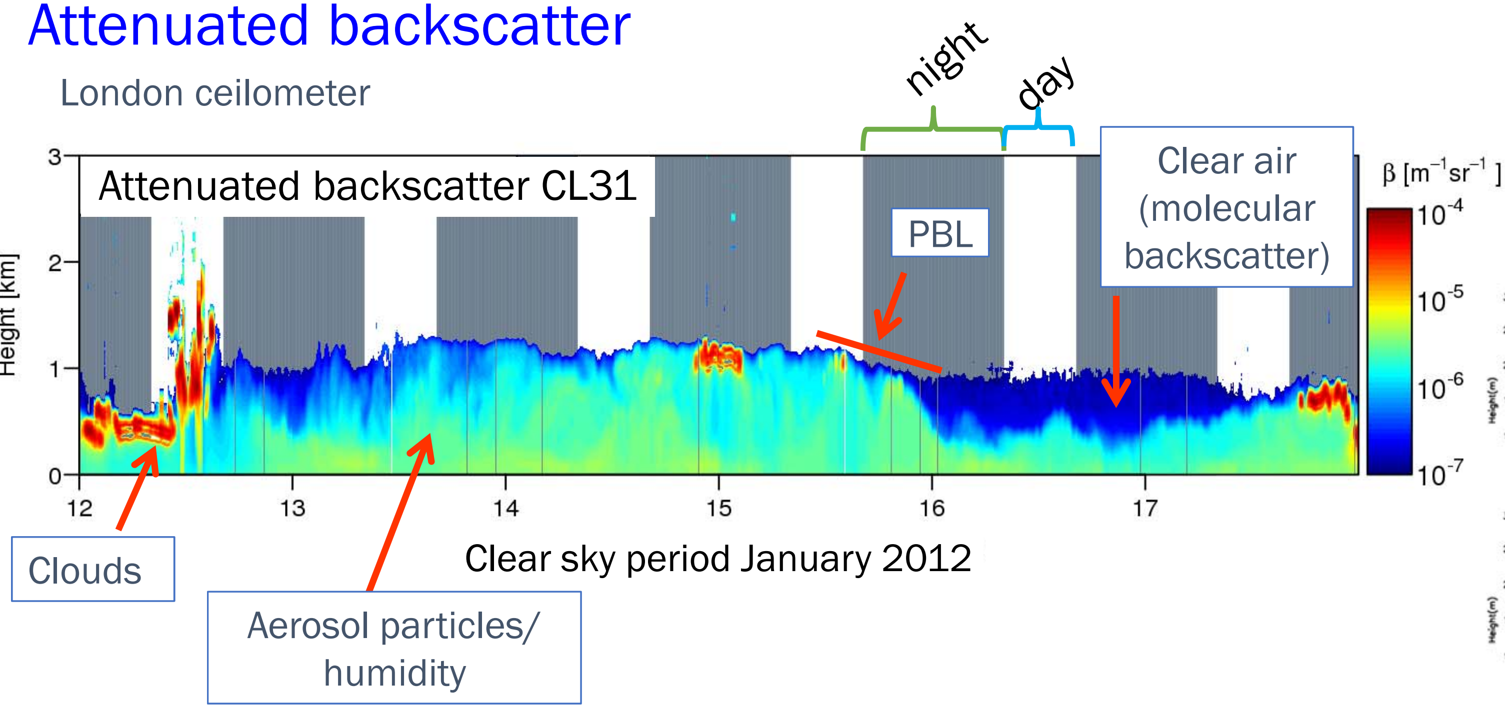
- Laser: attenuated backscatter β
  - ✓ Cloud/ice droplets
  - ✓ Aerosols
  - ✓ Molecules / atmospheric gases
  - ✓ Raw resolution: 10 m vertical, 15 s.

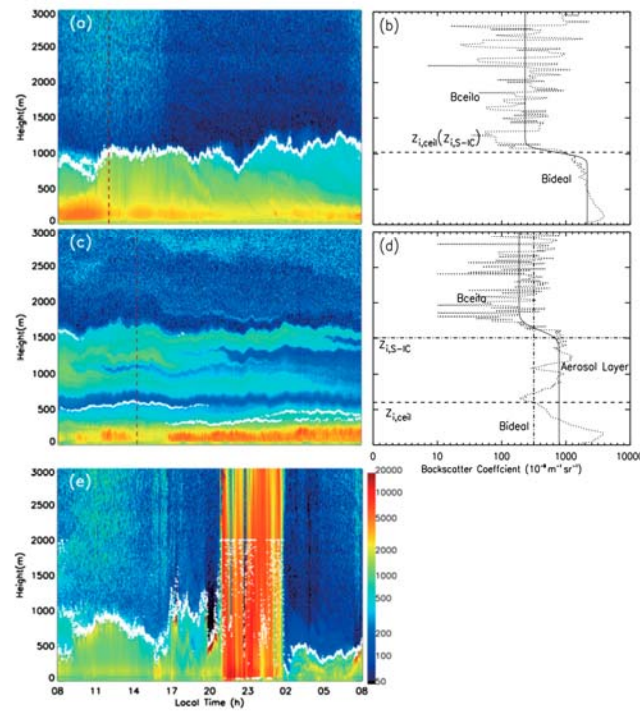



ALC @ London Air Quality Network (LAQN) site (NK)

# Attenuated backscatter

London ceilometer



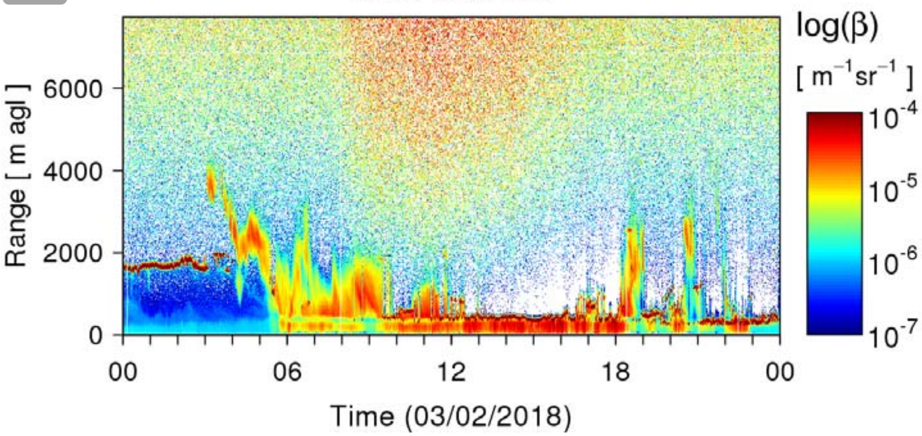




Signal:

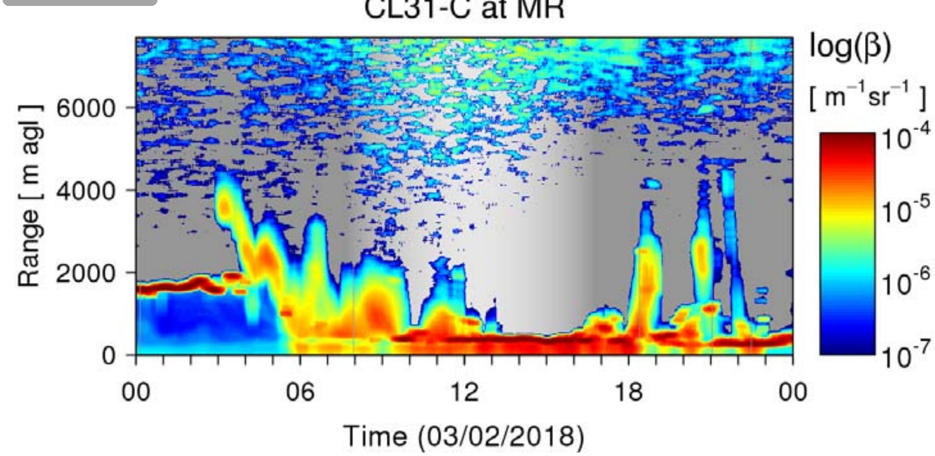
- Strong enough in PBL
- Above, only clouds (water & ice) and elevated aerosol layers detectable

# Ceilometer: initial data processing

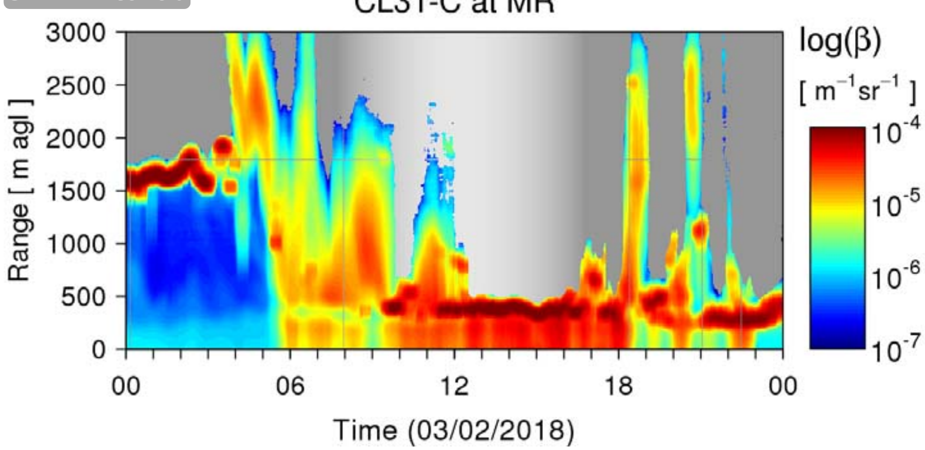
Raw



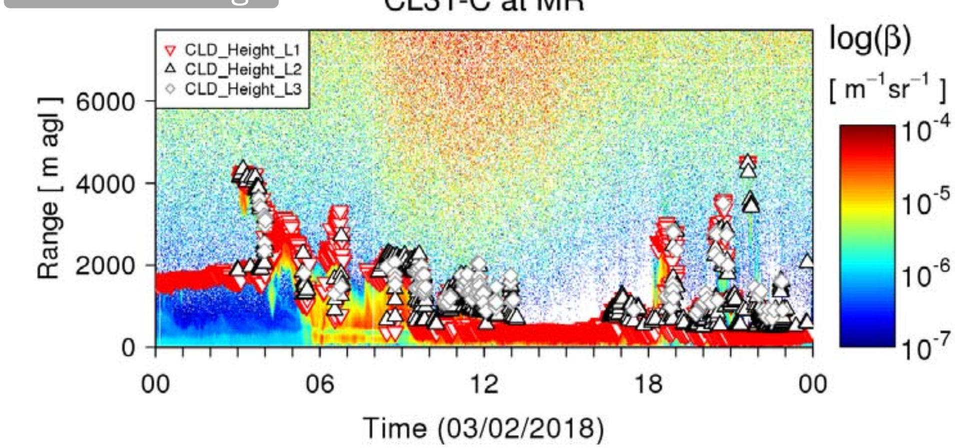

Smoothed




SNR Filtered



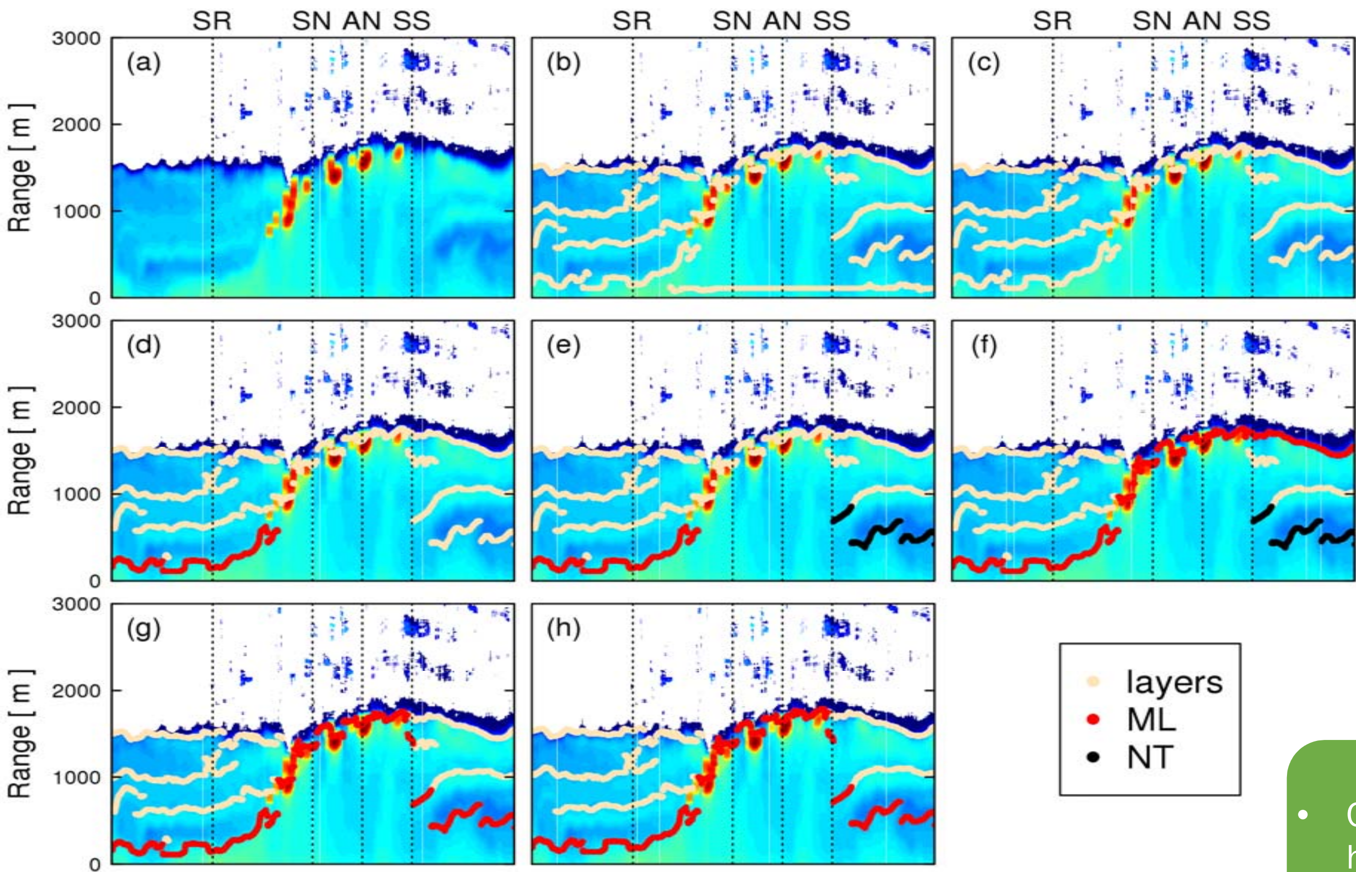

Cloud Base Height






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*

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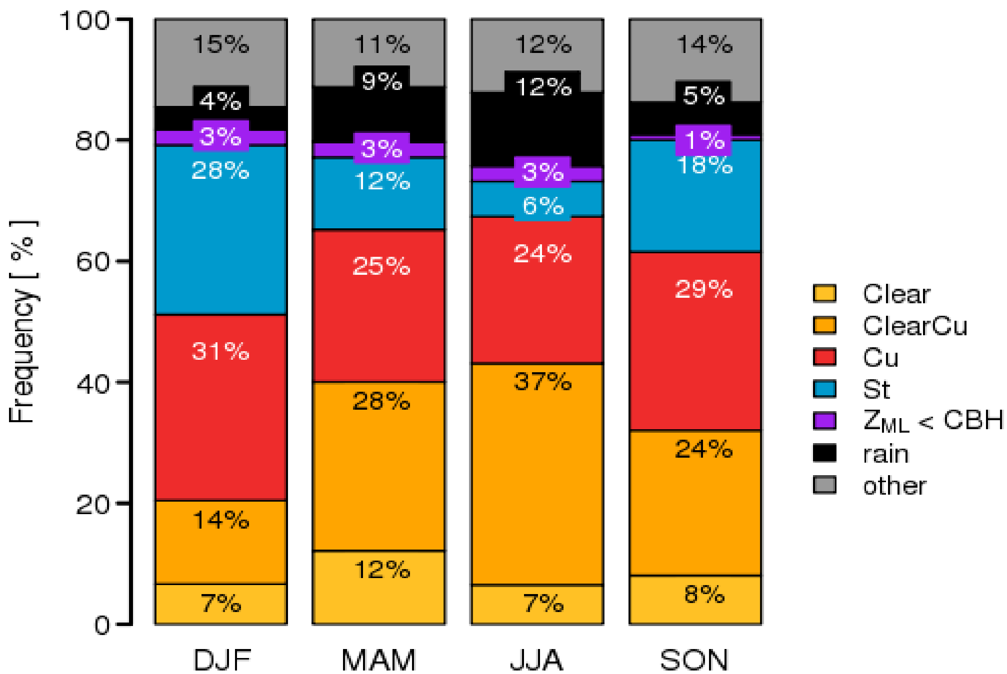
Kotthaus and Grimmond (2018a) QJRMS (mr)

# 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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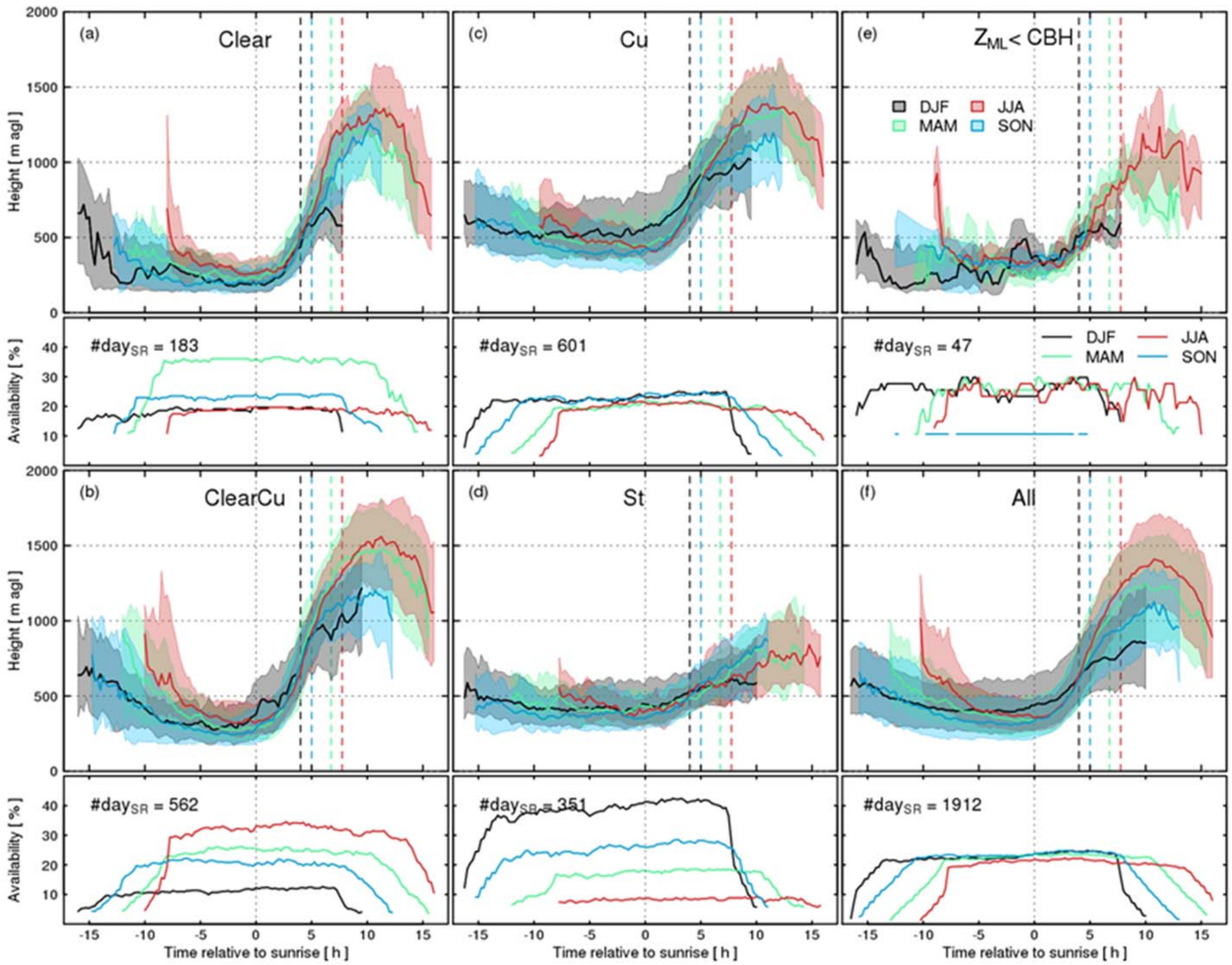
Kotthaus and Grimmond (2018b) QJRMS (mr)

# 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*

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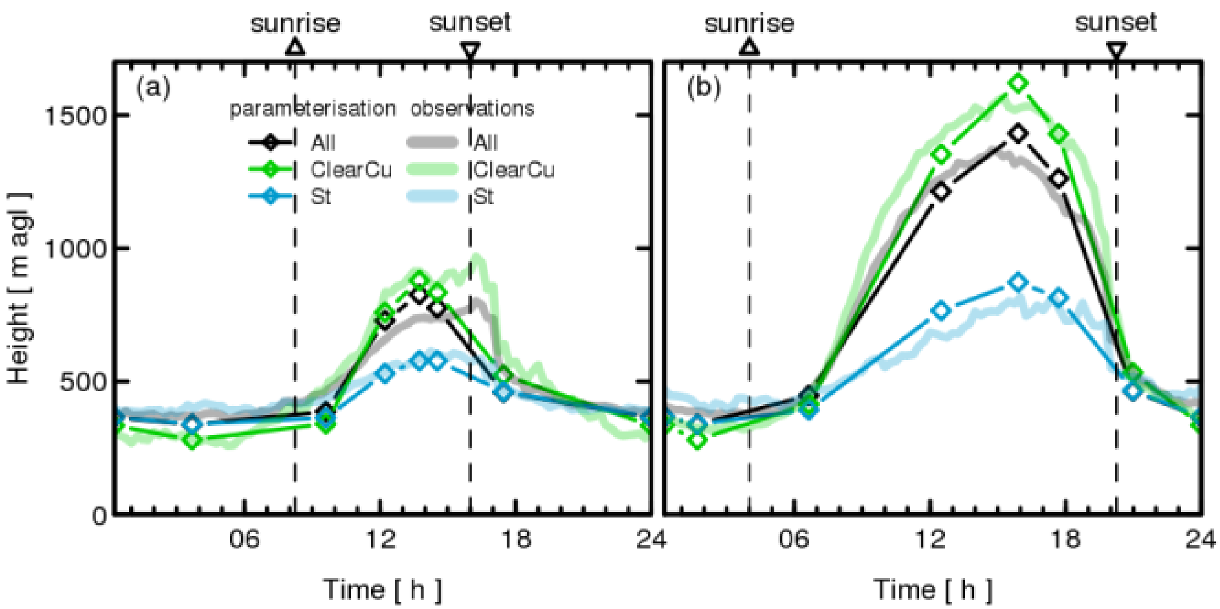
# MLH Simple parameterisation: function of cloud conditions and daylength

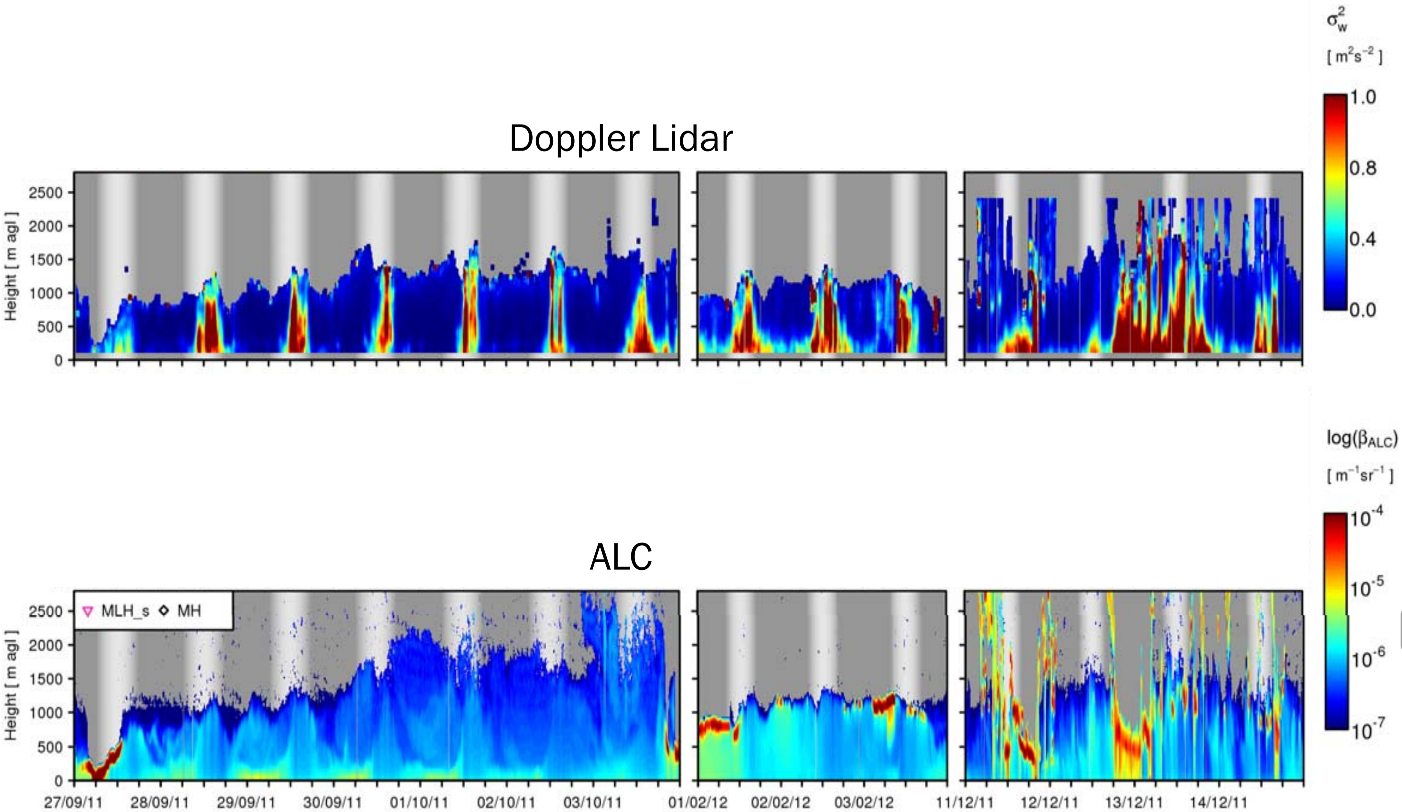



Winter solstice Summer solstice

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

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

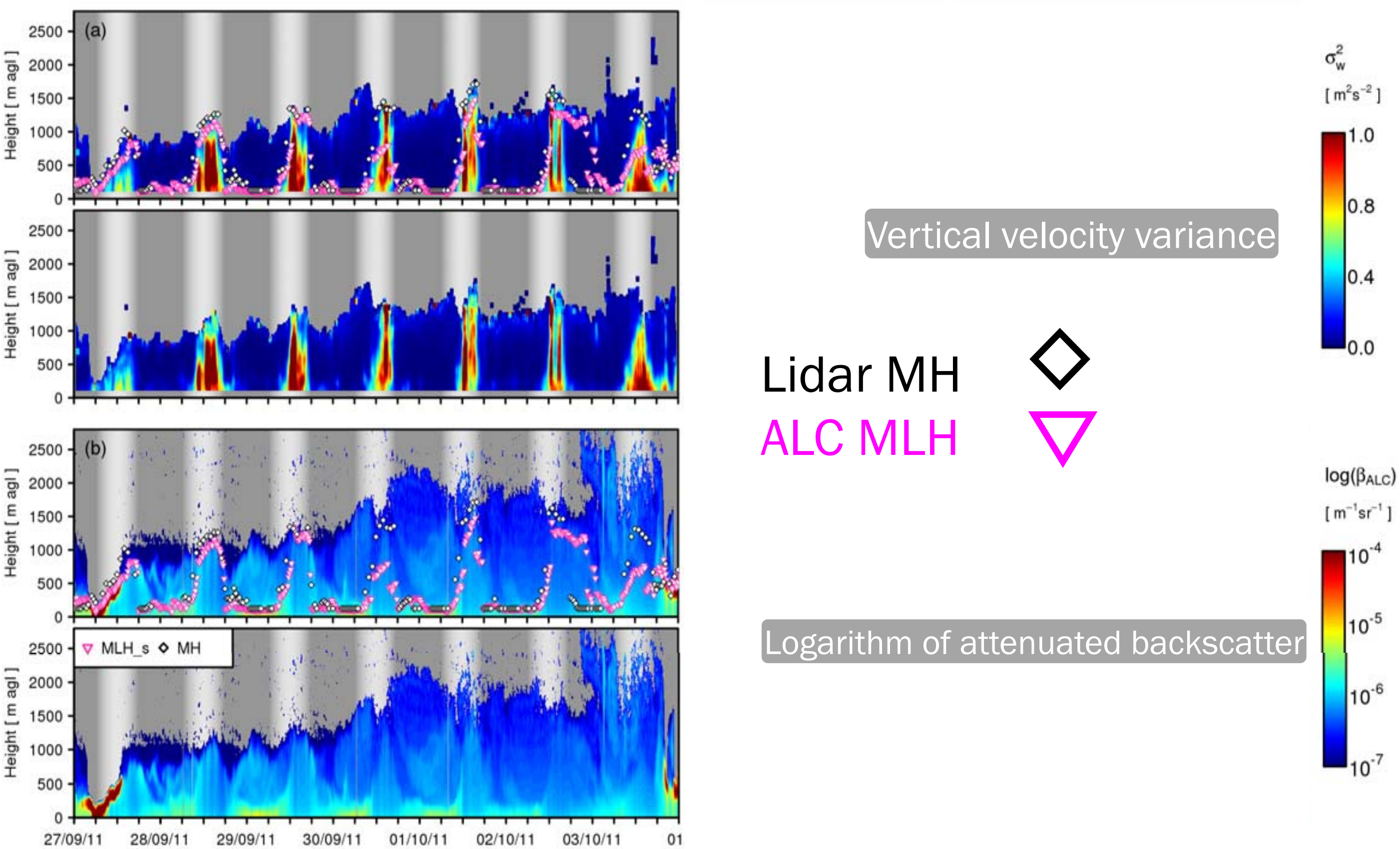



Vertical velocity variance

Logarithm of attenuated backscatter

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

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






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

# Diurnal and Seasonal Cycles

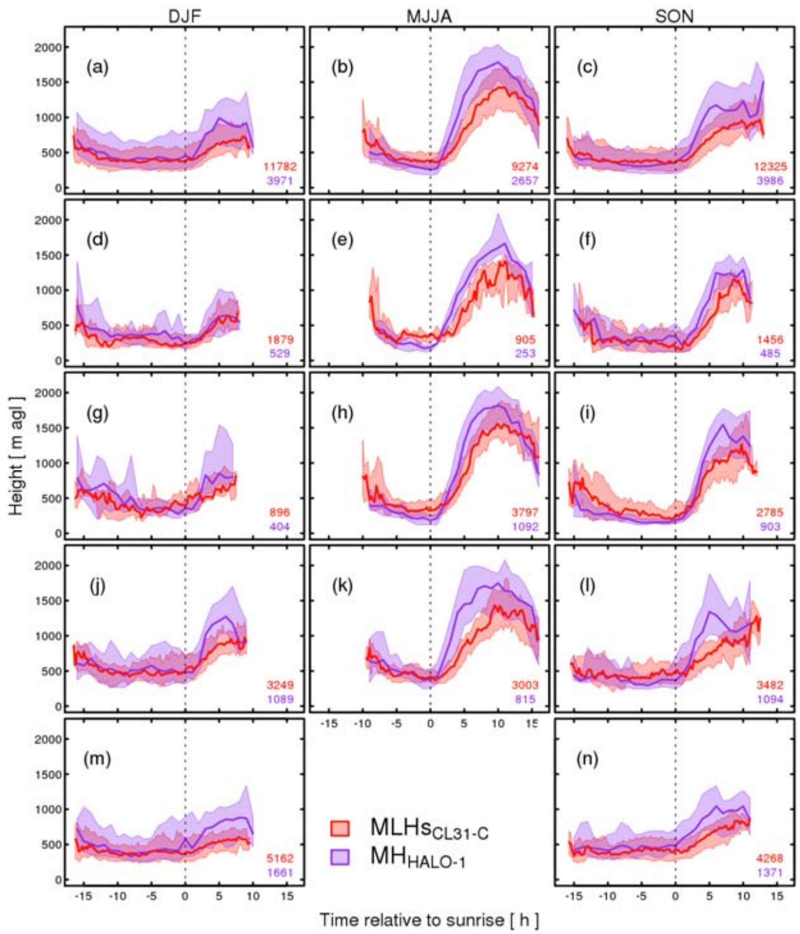
All days

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)

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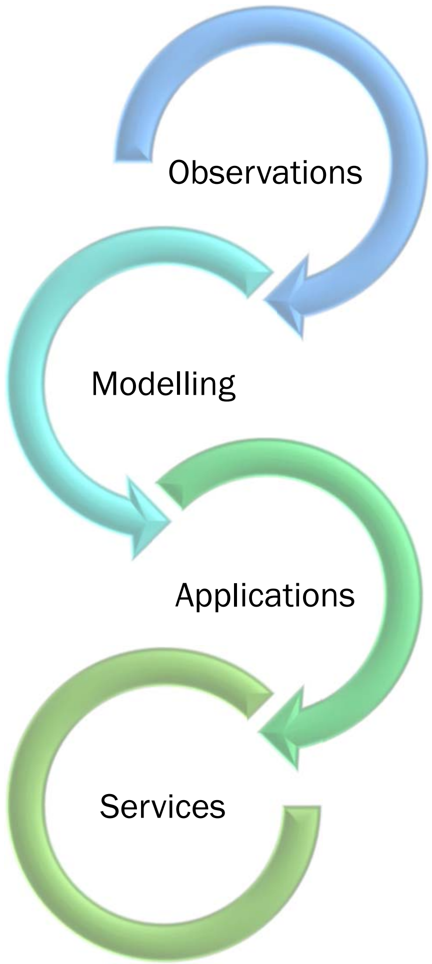
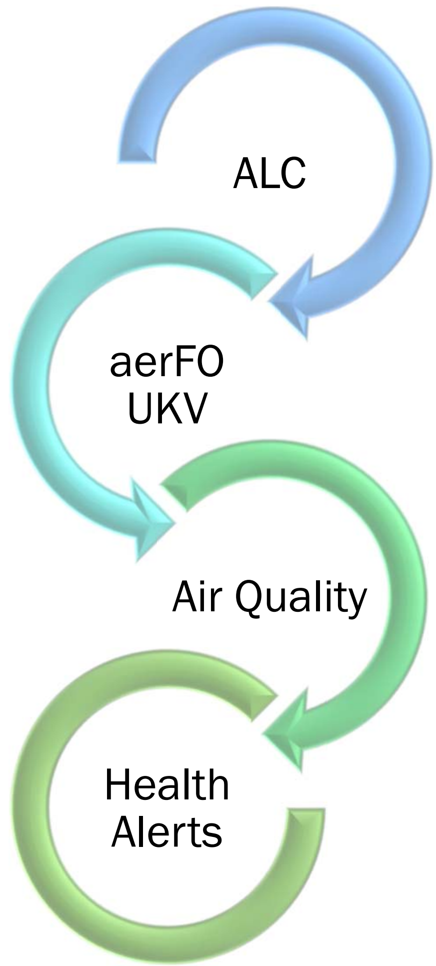
Kotthaus/Halios/Barlow/Grimmond (in prep.)

# Data Assimilation: Forward Operator for ALC attenuated backscatter



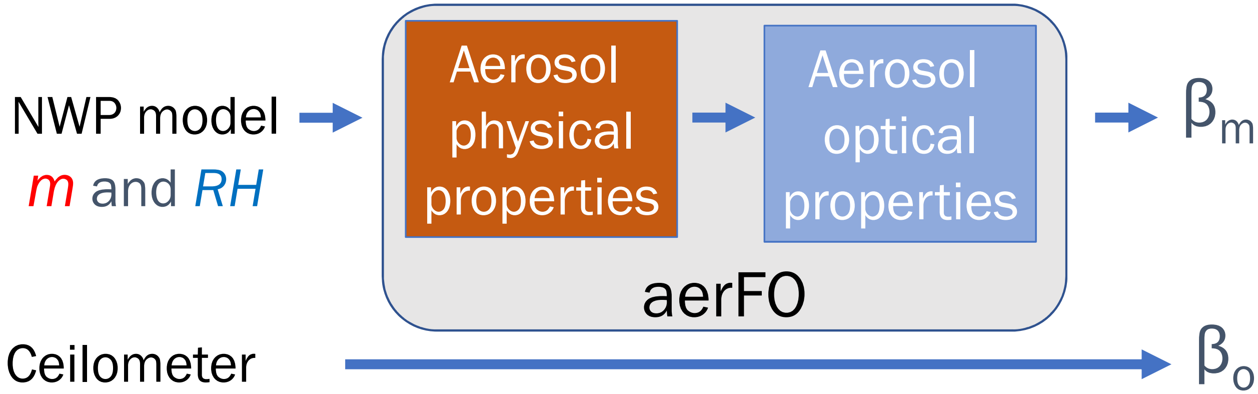



# Aerosol Forward Operator (aerFO): to estimate attenuated backscatter ($\beta_m$)

- **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

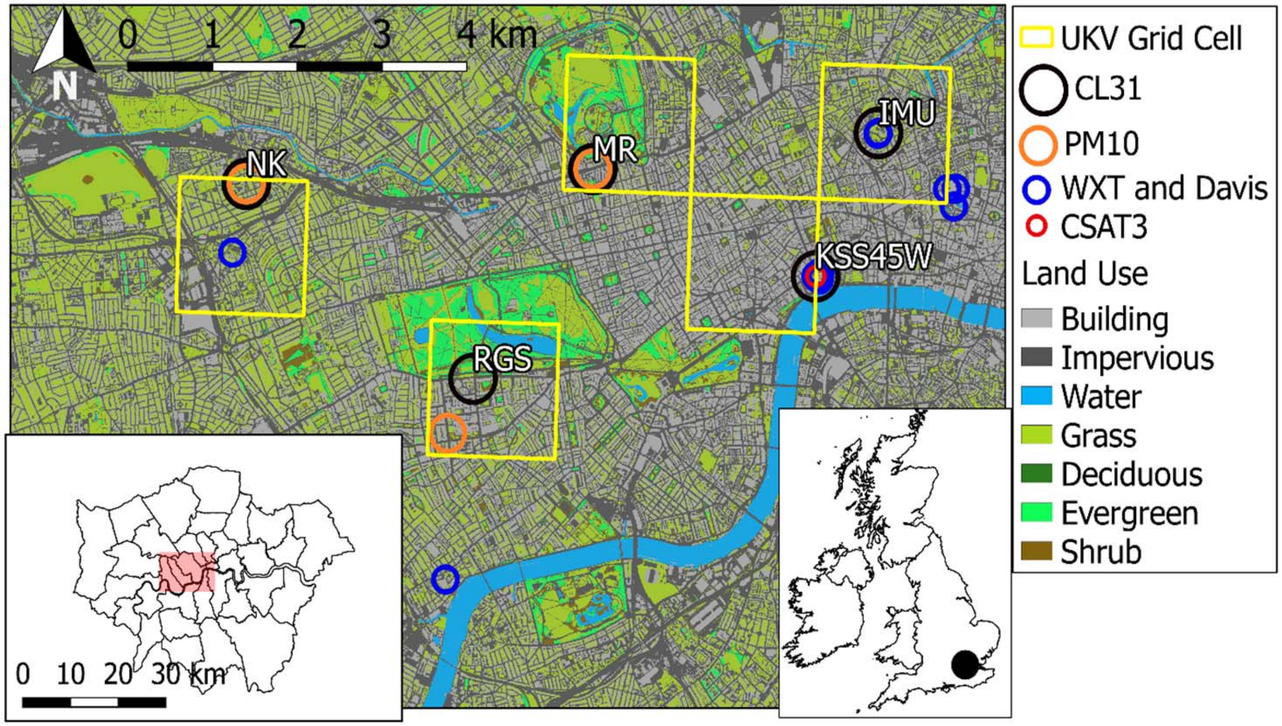
| Lidar ratio = 60 sr | Aerosols |
|---|---|
| Ammonium Nitrate | $NH_4NO_3$ |
| Ammonium Sulphate | $(NH_4)_2SO_4$ |
| Aged Fossil Fuel Organic Carbon | OC |




Warren et al. (in review)

# NWP and observation data

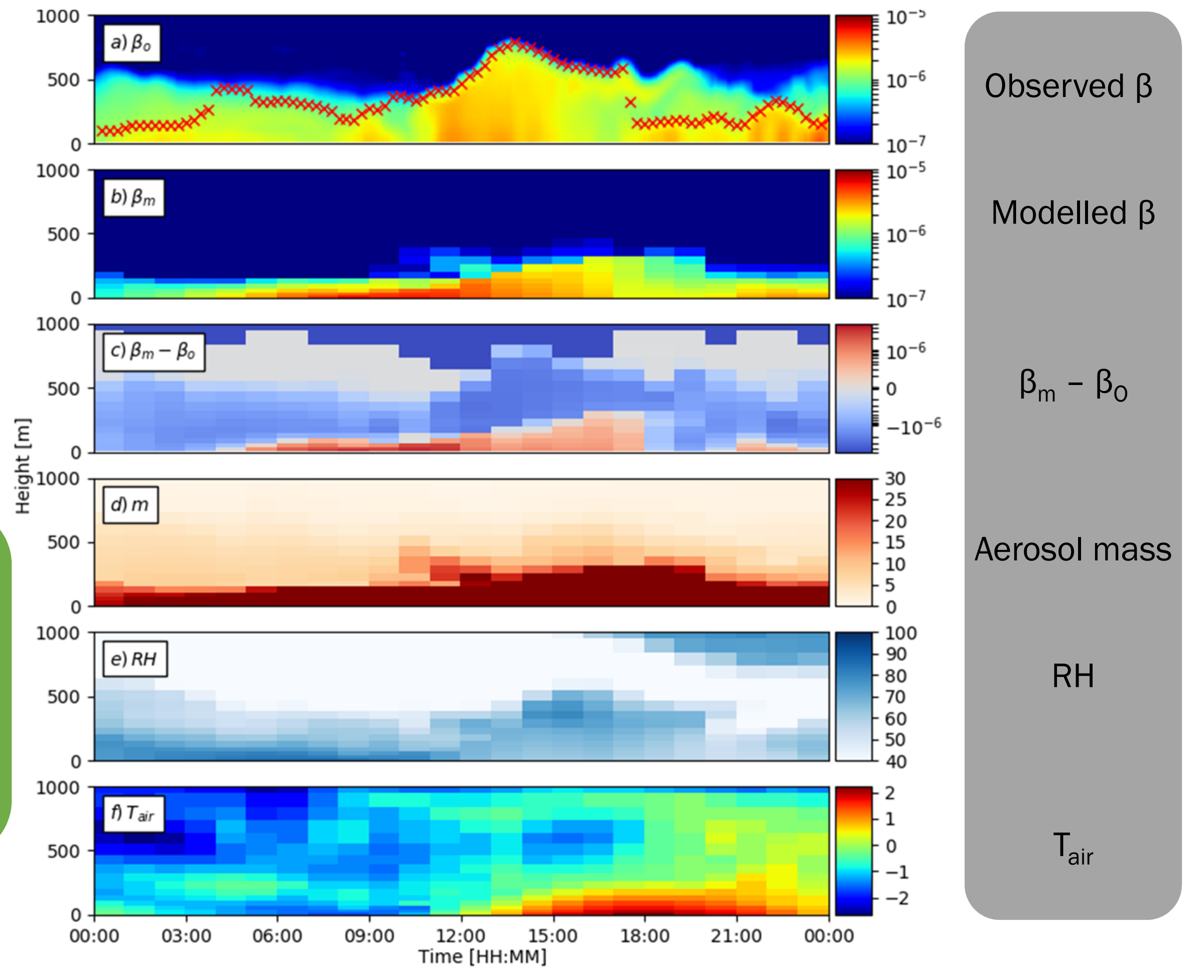
- 11 clear sky days between 5 Feb 2015 and 31 Dec 2016.
- NWP: **Met Office UKV** 1.5 km 21Z forecasts (3 h spin up, 1 h resolution)
- Observation: 4 Vaisala CL31 ceilometers (raw resolution 10 m vertical, 15 s)
  - Processed: moving average (25 min, 110 m, Kotthaus et al., 2016) and calibrated (Hopkin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

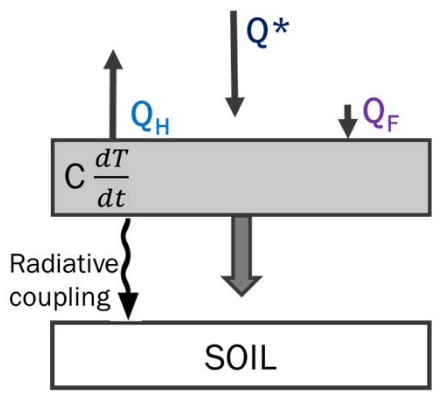



- Almost persistently high $\beta_m$ near the surface
- Aerosol: insufficiently mixed in the vertical due to **lack of aerosol dispersion**
- Earlier dates – could identify emission inventory problems

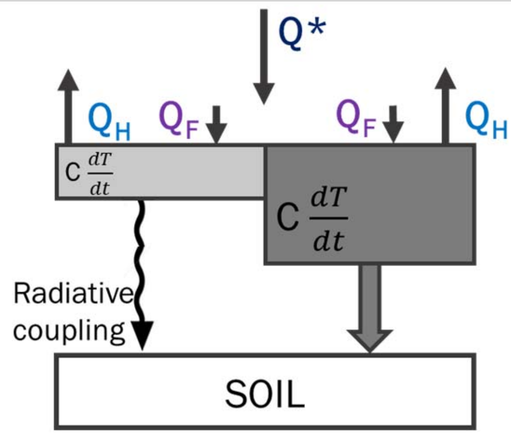
Warren et al. (in review)

# To improve mixing new urban land surface scheme in UKV

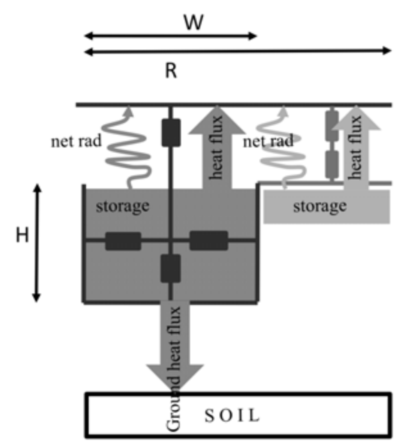
| | Best 1 - Tile | MORUSES |
|---|---|---|
| Surface | 1 bulk | Canyon and roof |
| $Q^*$ | Bulk α and ε | Material properties with form |
| $Q_F$ | Prescribed | |
| $Q_E$ | Non-urban tile | |
| $Q_H$ | Thermal roughness length | Resistance network |
| $C\frac{dT}{dt}$ | 1 component | 2 components |




Best et al. (2004)




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

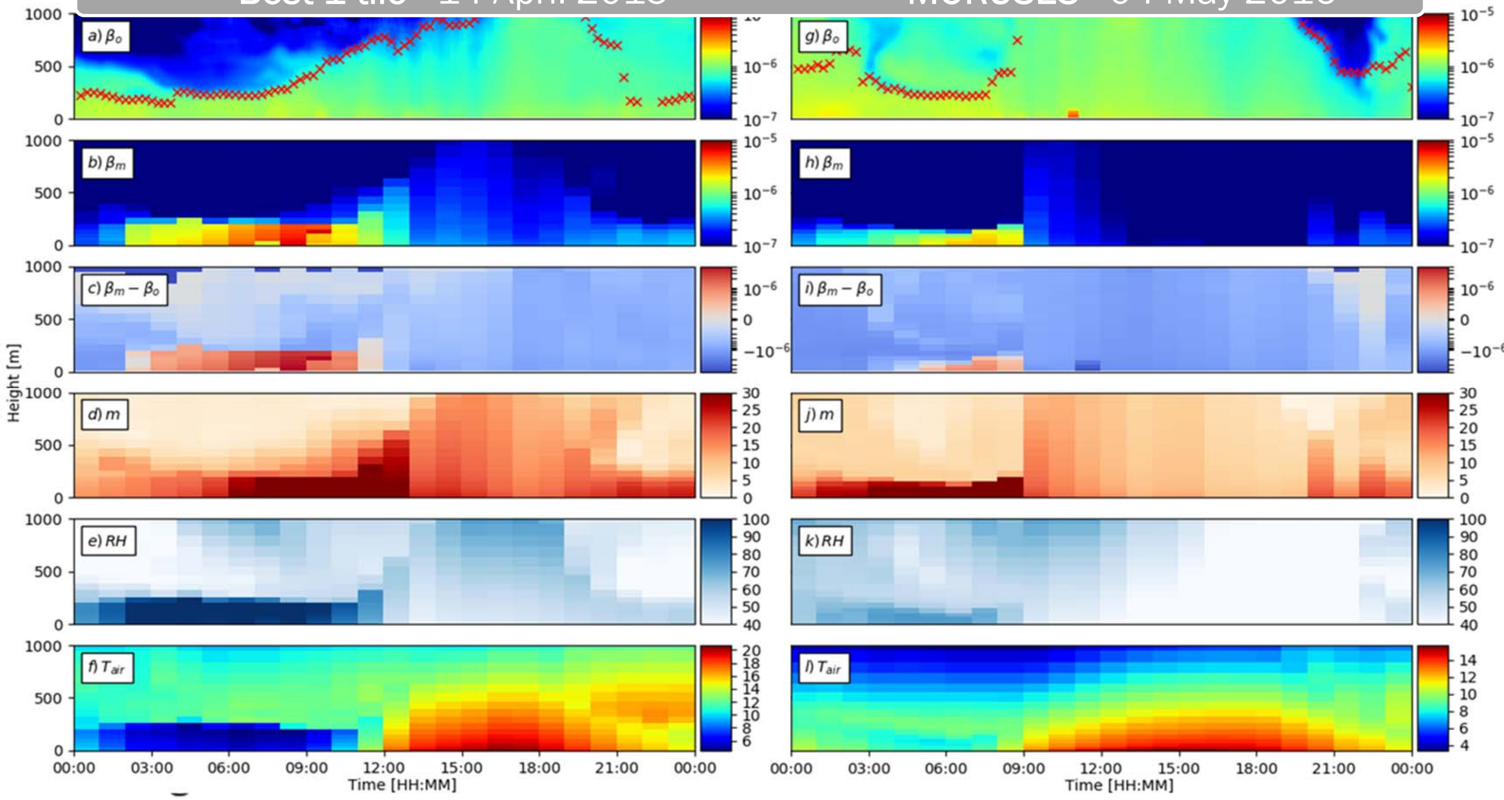


# Impact of changing model dynamics on $\beta_m$ as

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

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

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




Observed β

Modelled β

$\beta_m - \beta_O$

Aerosol mass

RH

$T_{air}$

Warren et al. (in review)

# Fluxes: EC - long term measurements

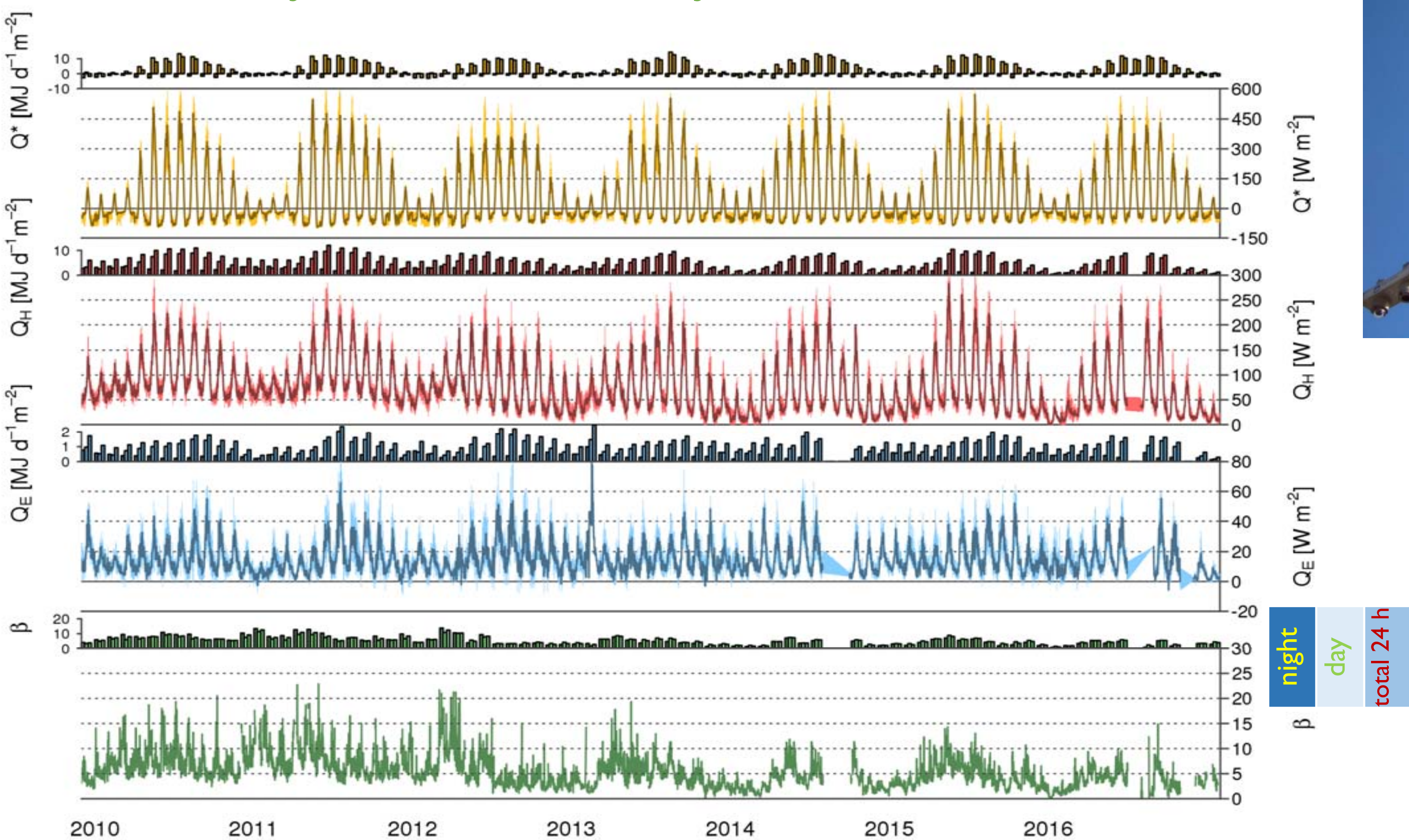
## Monthly Median Diurnal Cycle, shaded IQR, KSS

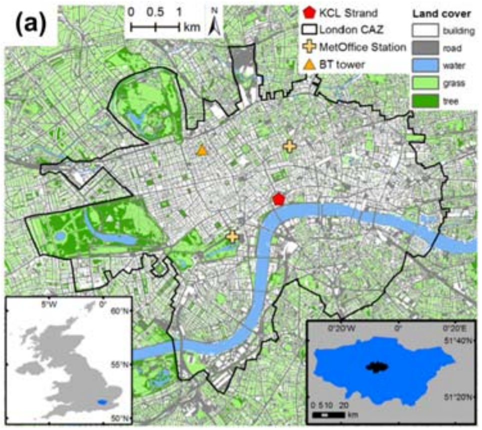
Q*

$Q_H$

$Q_E$

β

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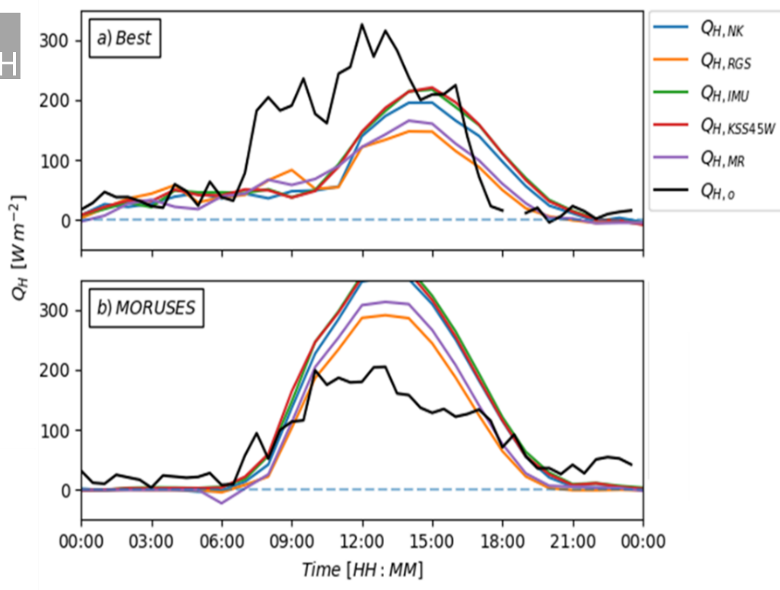
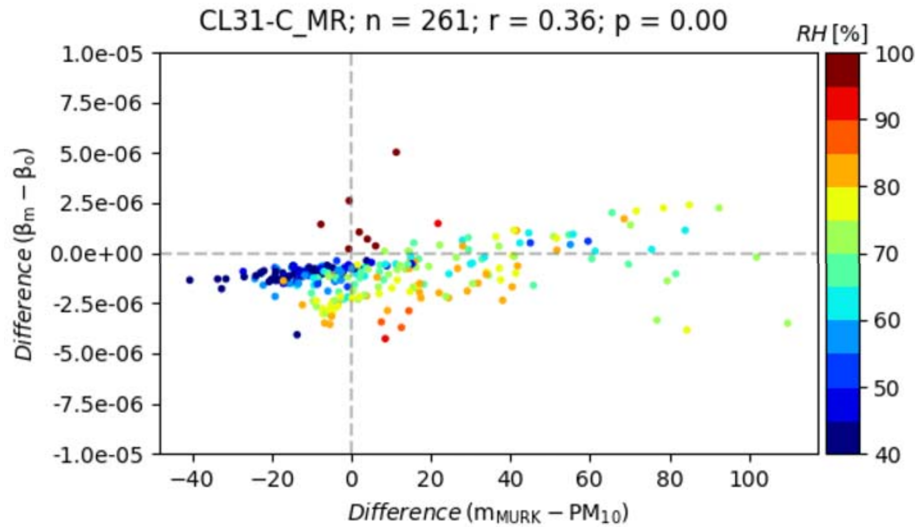
*Kotthaus & Grimmond (2014a) Urban Climate, Kotthaus and Grimmond (in prep).*

# 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
- $\beta_m$ - 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).

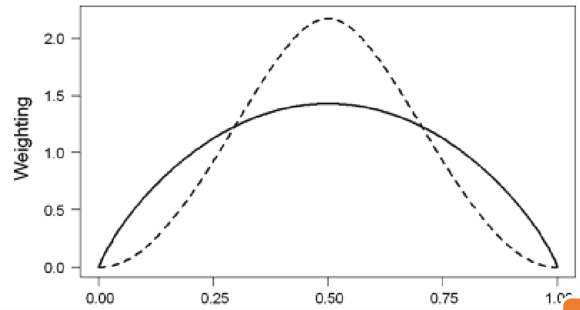
## Software tools

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

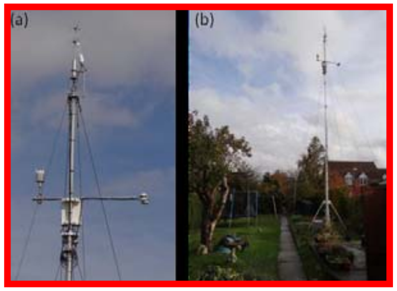
## Our research

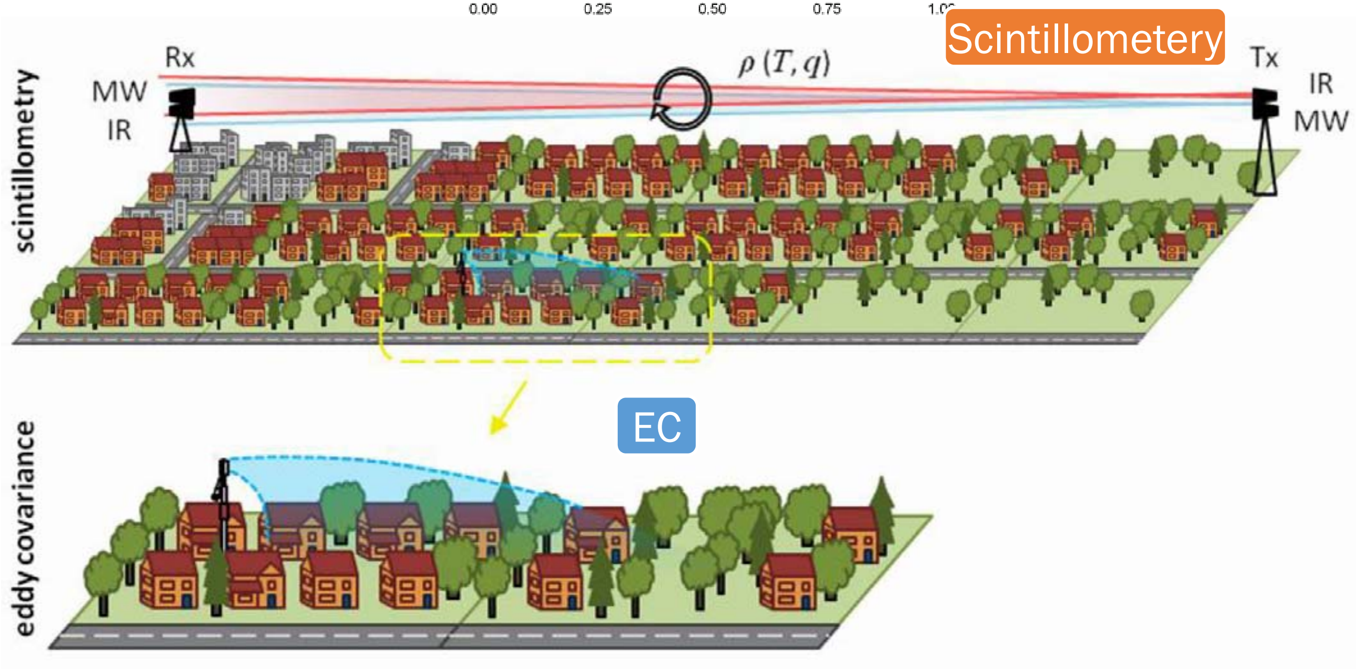
This page is maintained by the Urban micrometeorology research group at the University of Reading, UK.

# Scintillometry – another technique for turbulent heat fluxes



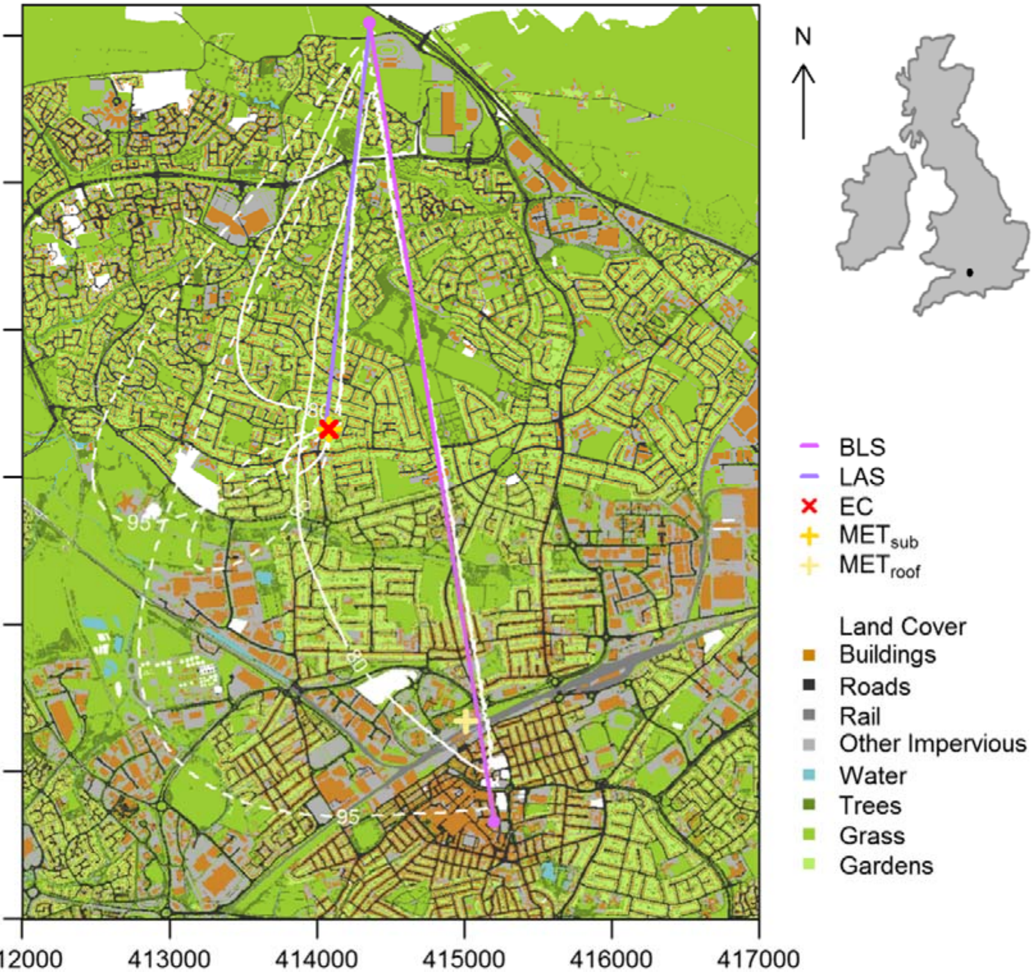





Ward et al. (2011) BLM; Ward (2013)

# Multi-scale Measurements of $Q_H$



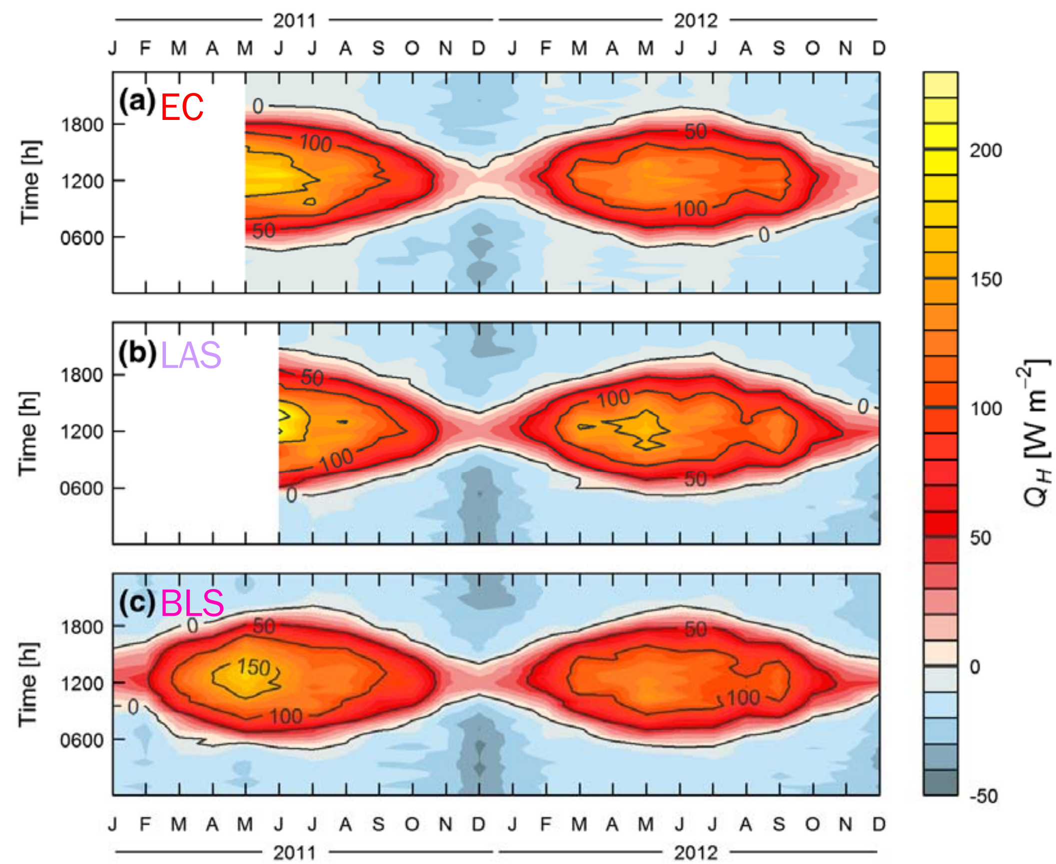




**Fig. 4** Temporal variation of monthly mean diurnal cycles of sensible heat fluxes from (**a**) eddy covariance, (**b**) the LAS and (**c**) the BLS

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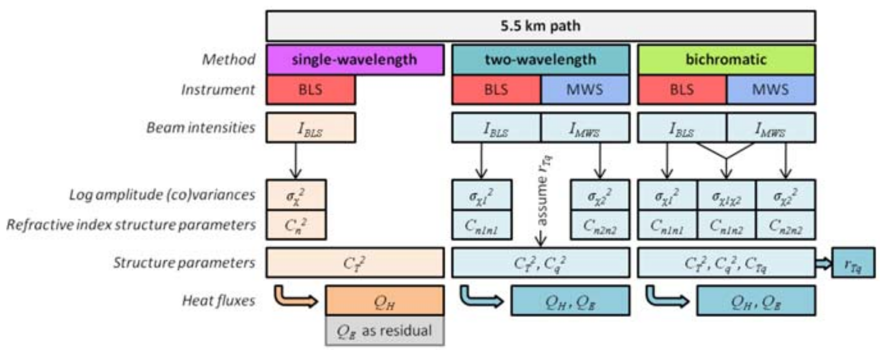
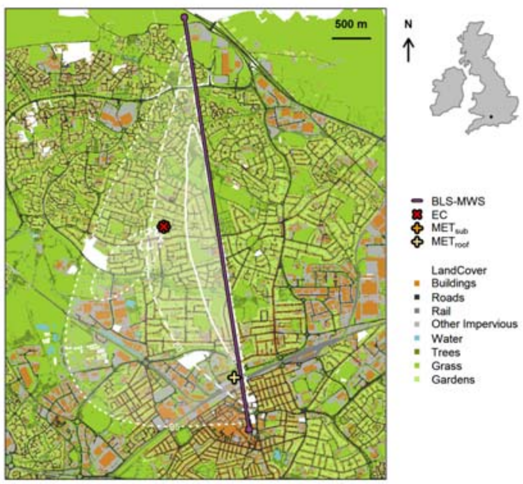
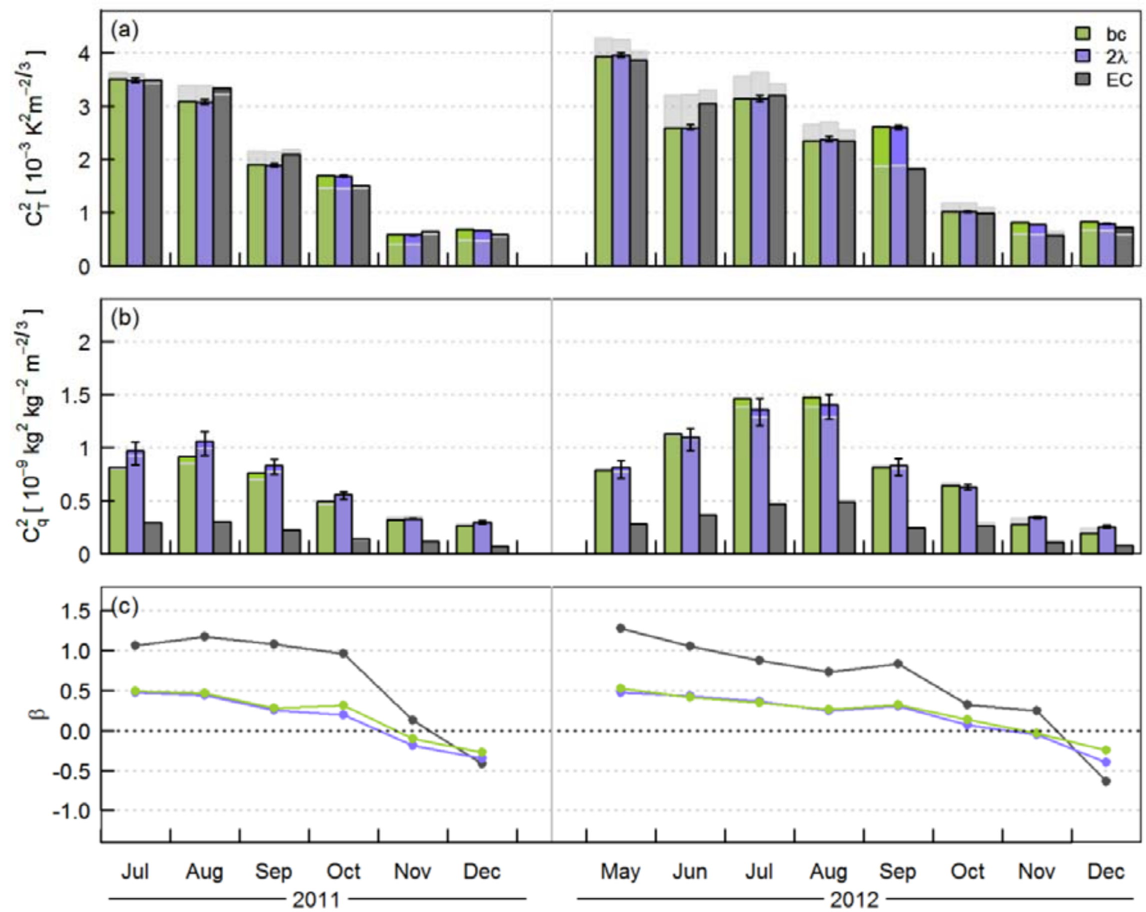
*Ward et al. (2014) BLM*

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

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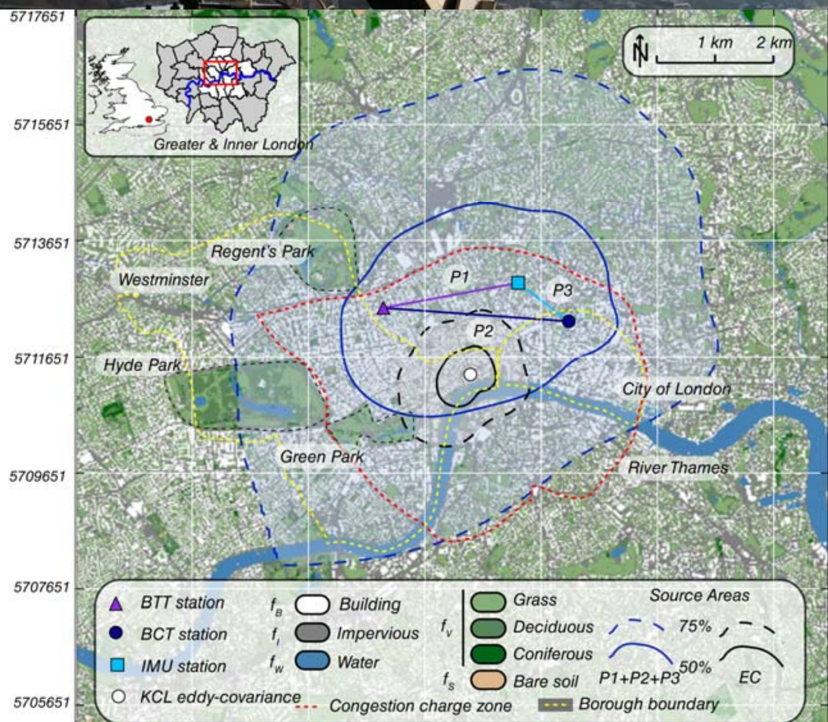
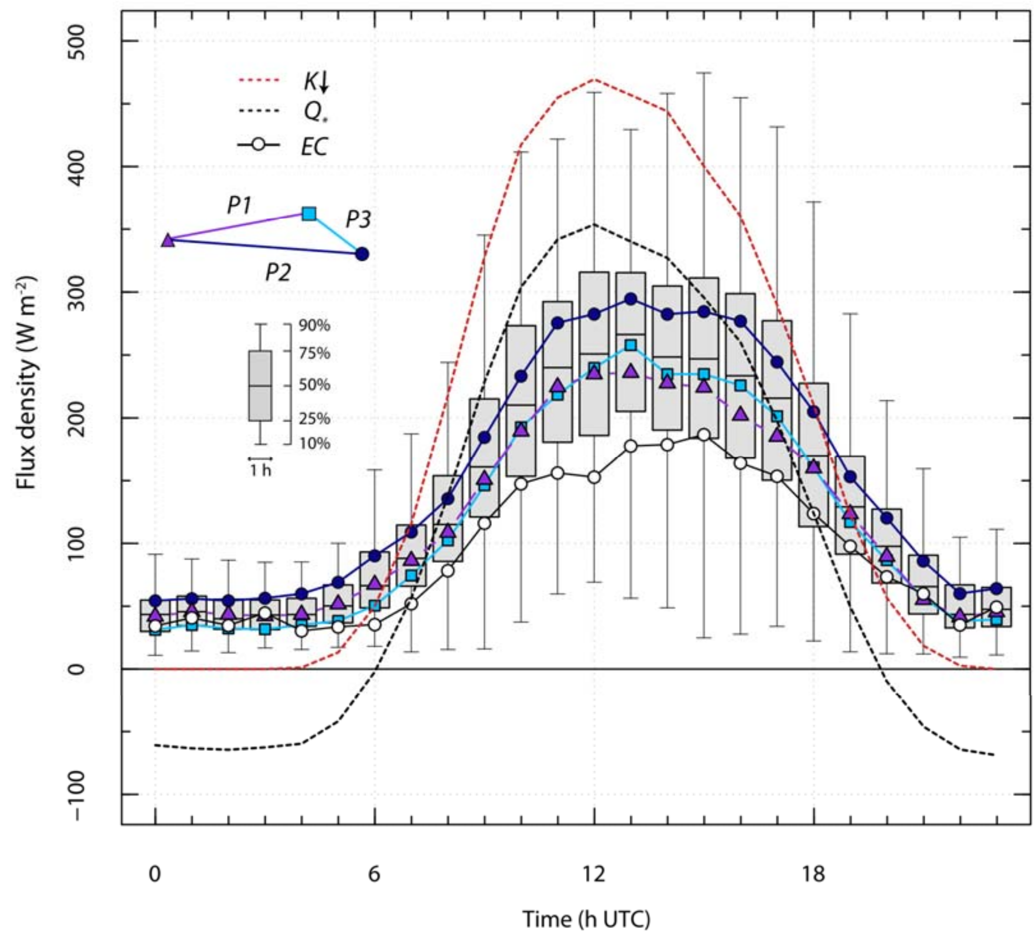
Ward et al. (2015a) Atmos. Meas. Tech., 8, 1385–1405 doi:10.5194/amt-8-1385-2015

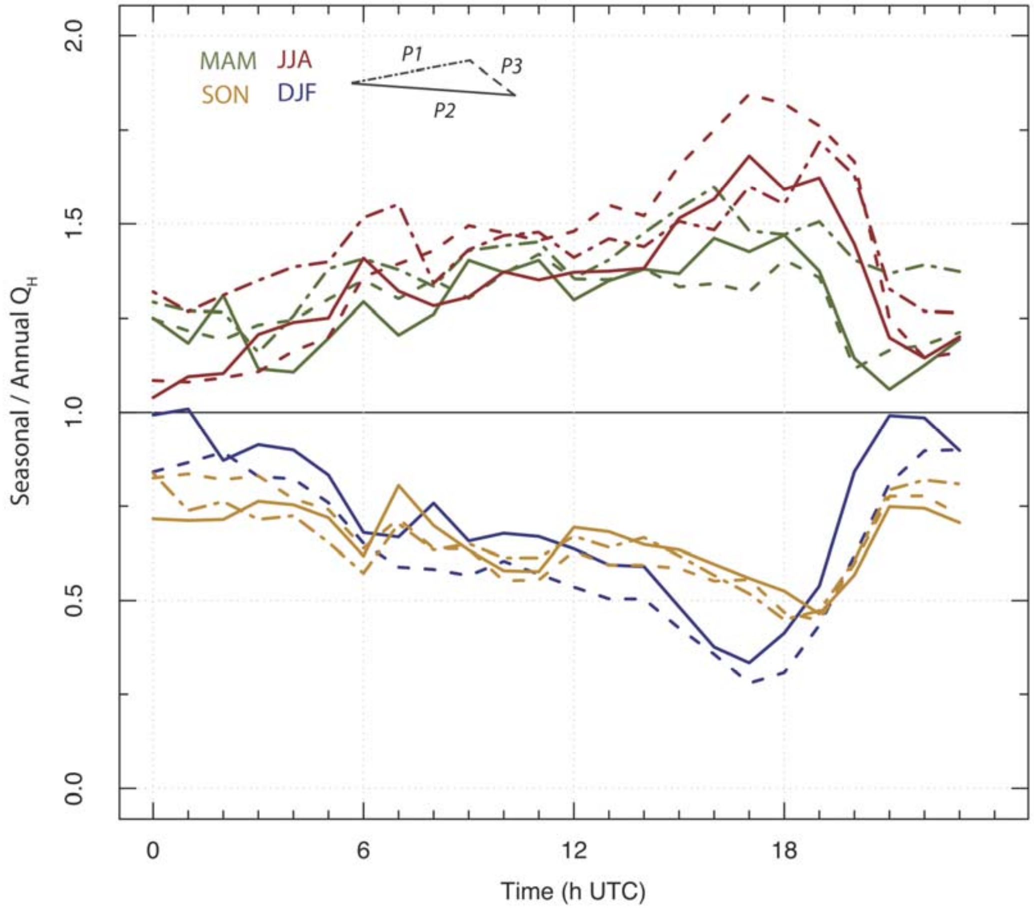
# Sctinillometry – 3 paths (London)

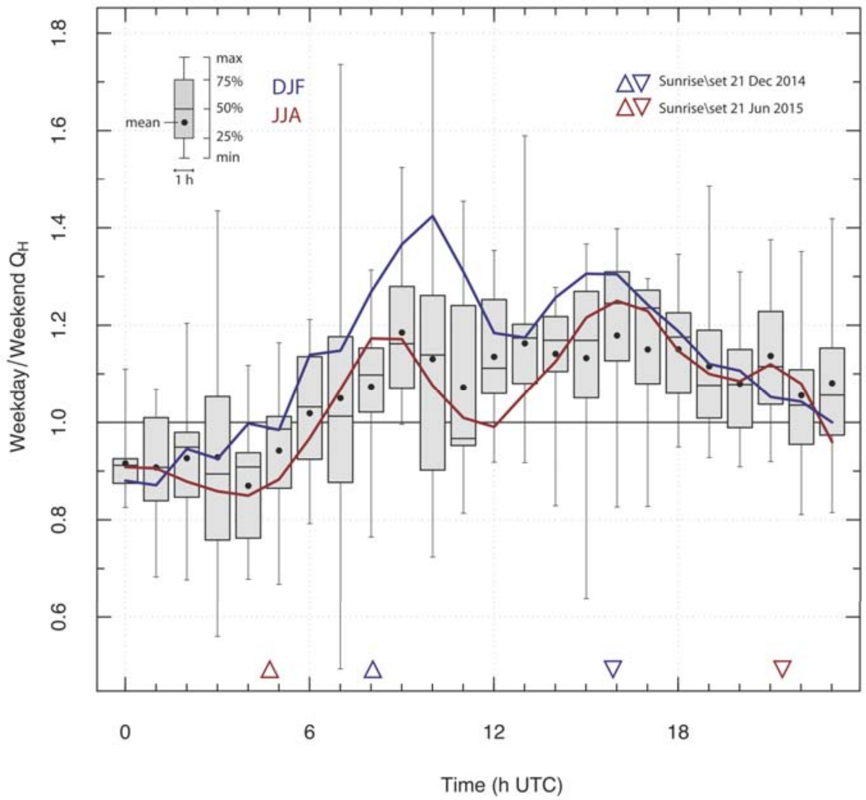




Crawford et al. 2017 QJRMS doi:10.1002/qj.2967

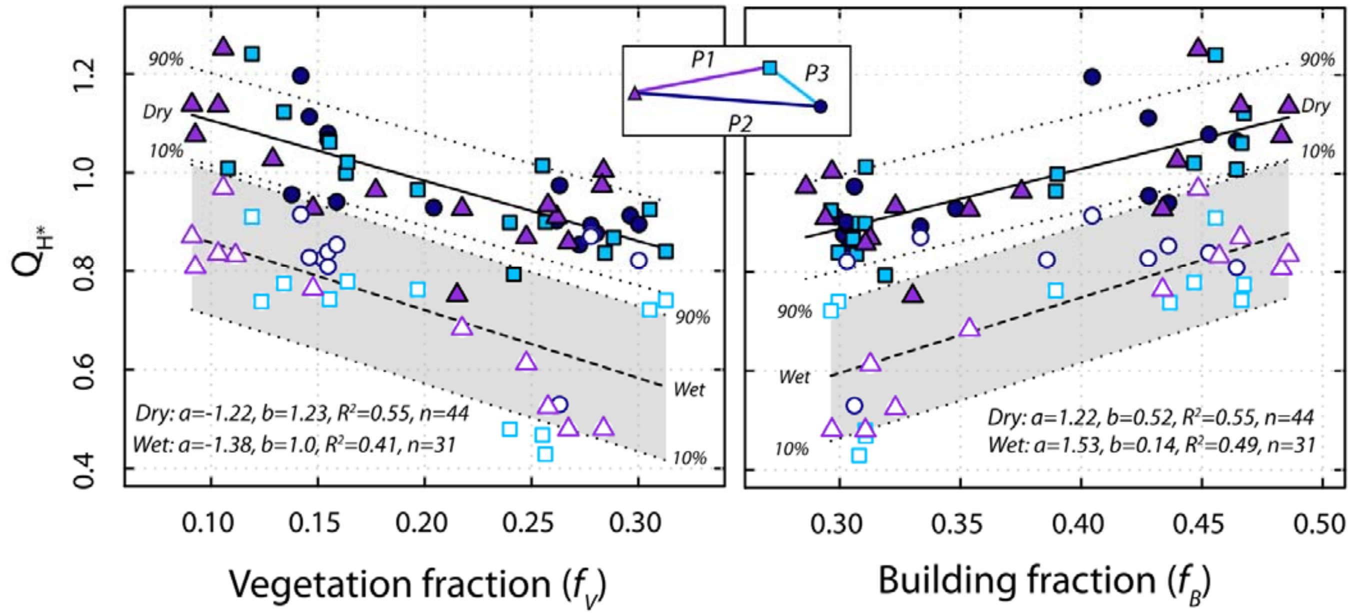
# Spatial Variability with Season by time of day -------- and day of week




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

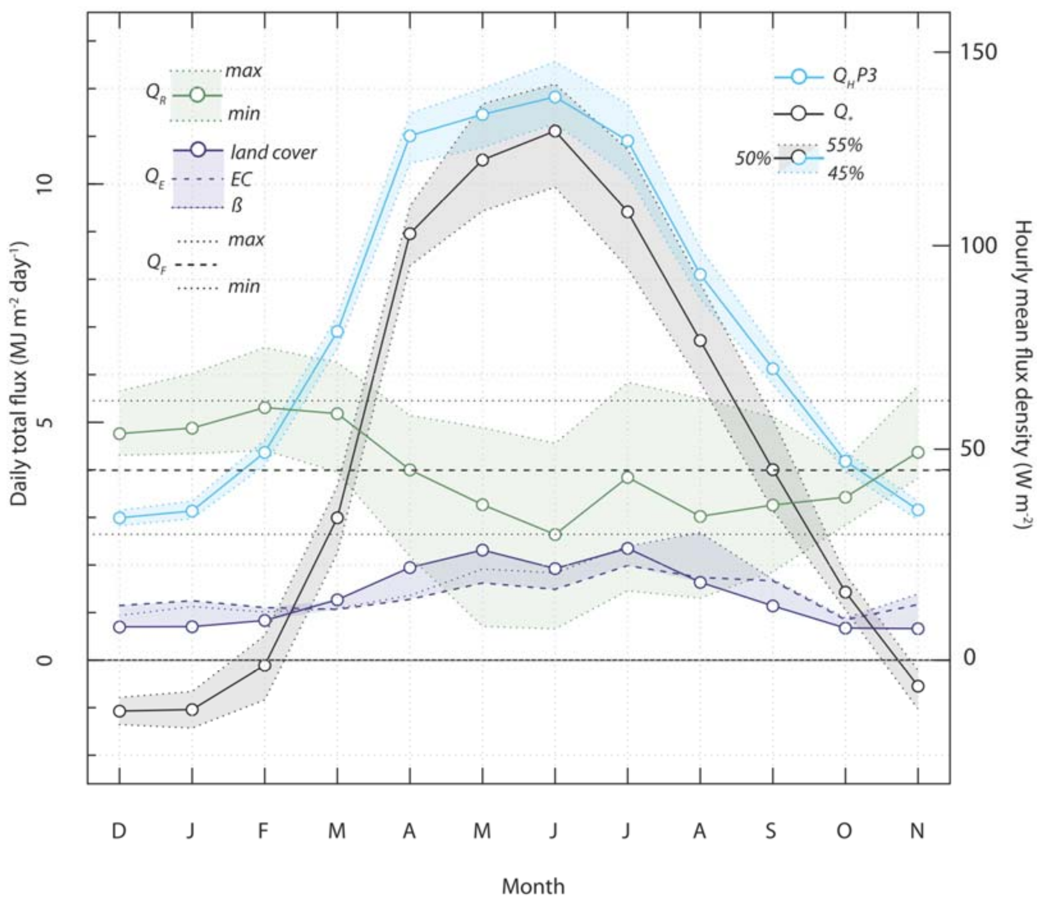
# Normalized variations by surface wetness and surface cover





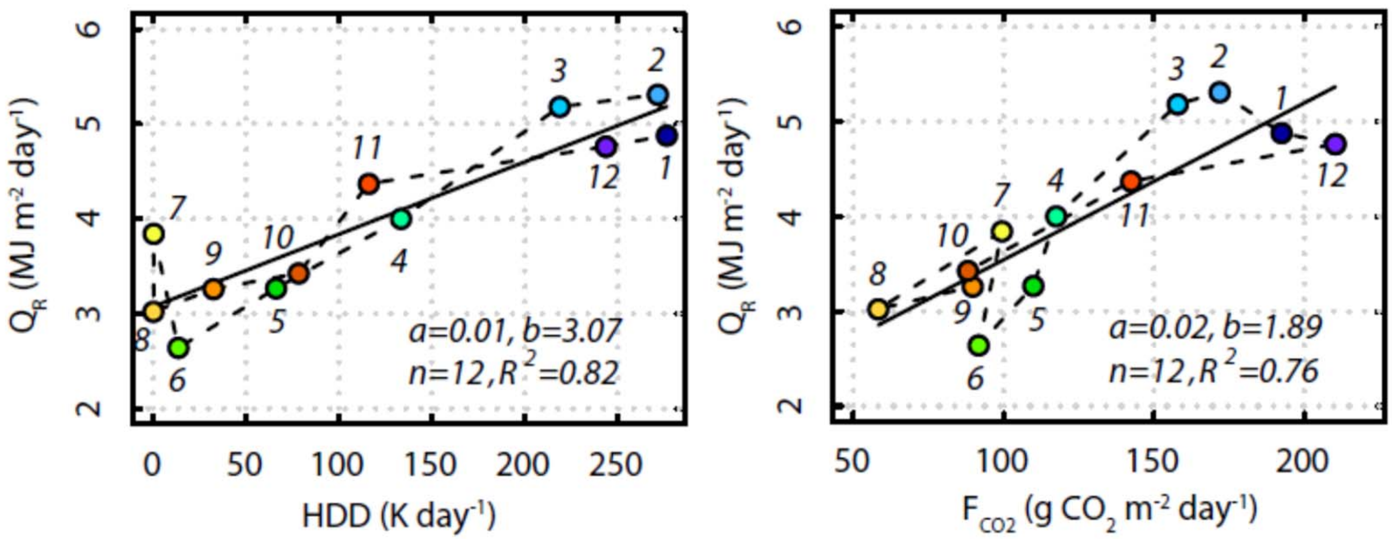

Crawford et al. 2017 QJRMS doi:10.1002/qj.2967

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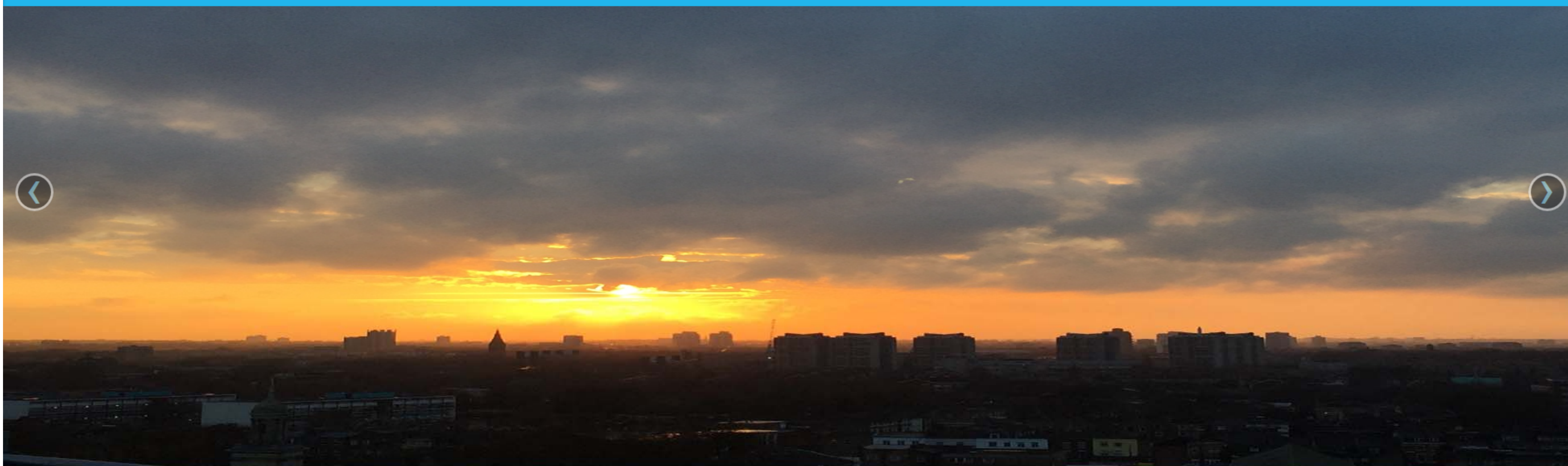
*Crawford et al. 2017 QJRMS*, 143, 703, B, 817–833 *doi:10.1002/qj.2967*

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

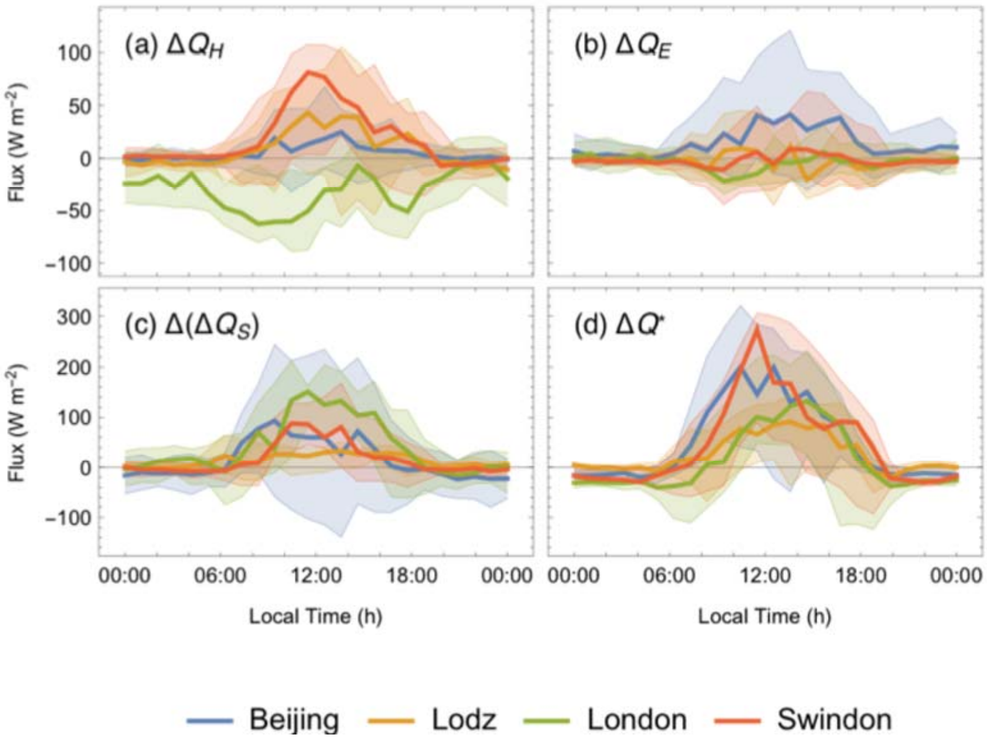
Information and download instructions for the UMEP, SUEWS and SOLWEIG models to analyse and predict urban micro-meteorological environmental conditions.

## 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

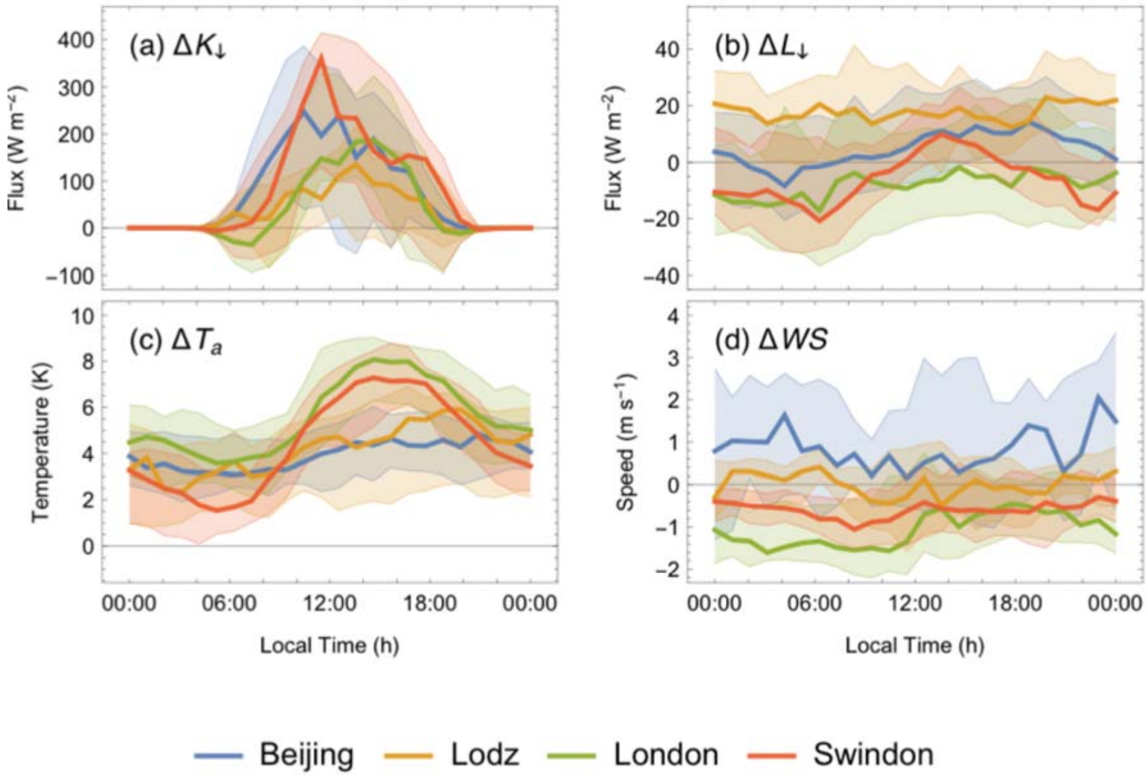
$$Q^* - \Delta Q_S = Q_H + Q_E$$




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

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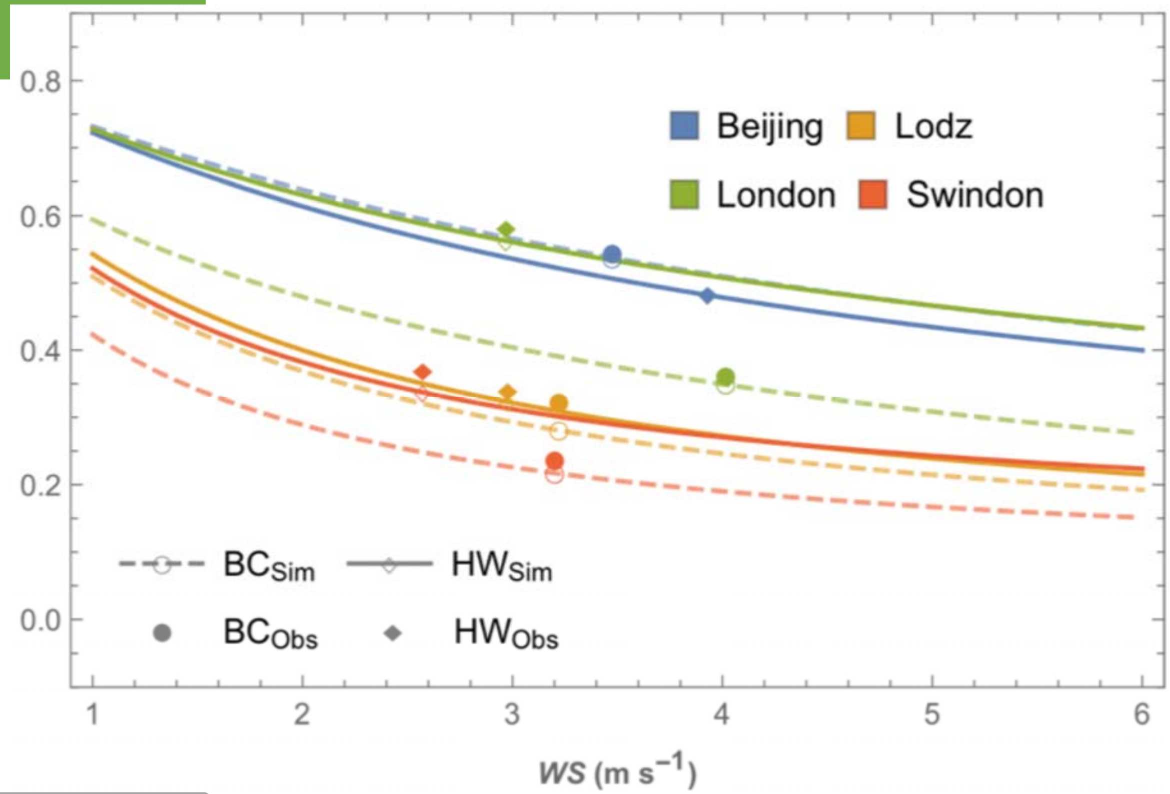
Sun et al. (2017) ERL doi:10.1088/1748-9326/aa922a

# Impacts of Wind Speed on Heat Storage Ratio: AnOHM simulations

- Good agreement: <u>obs</u>ervations & AnOHM <u>sim</u>ulations
  - HW- heat wave BC – before HW conditions
- Higher wind speed leads to decreased $rQ_S$
  - Enhanced turbulent transport
  - Decreased surface temperature

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

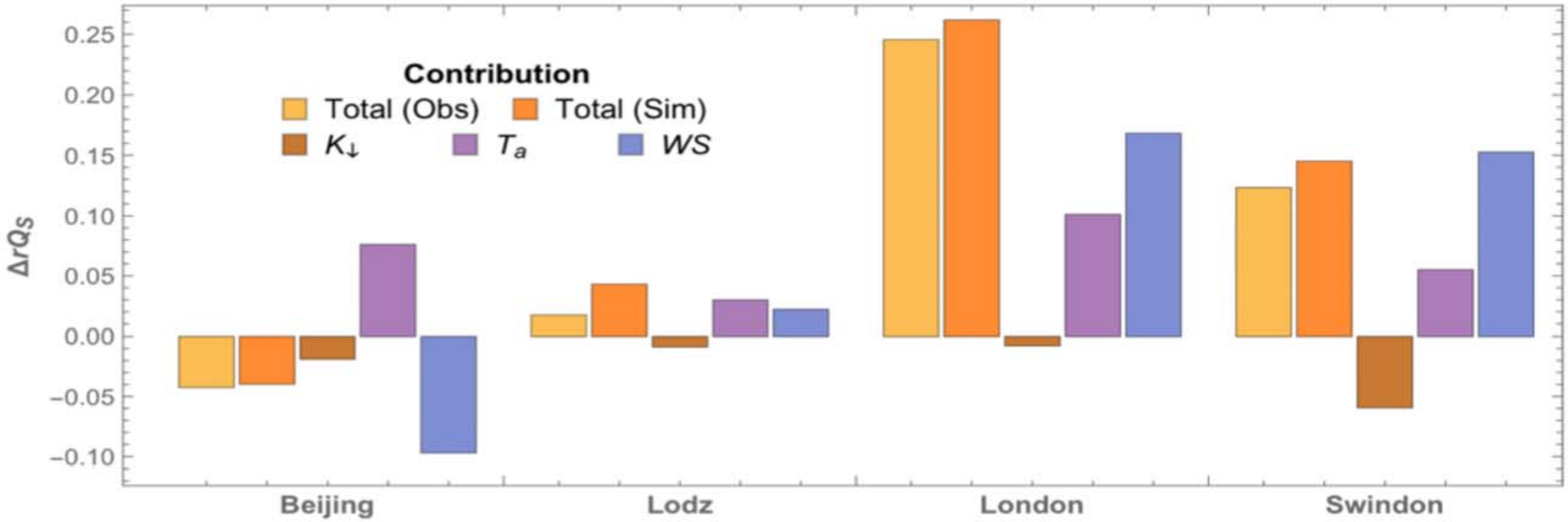





Sun et al. (2017) ERL doi:10.1088/1748-9326/aa922a

# Attribution of Heat Storage Ratio

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

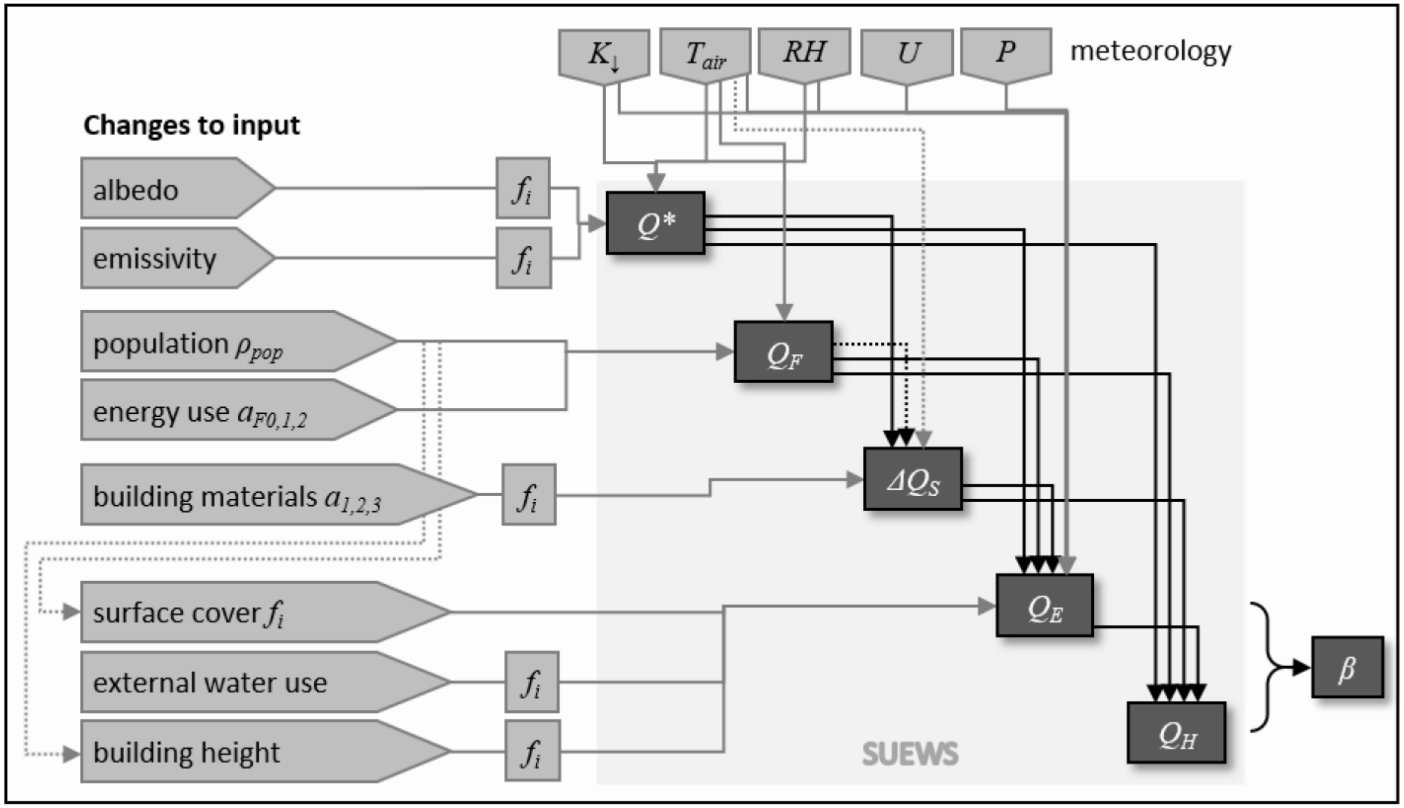



Wind speed: key determinant of heat wave-induced changes in storage heat



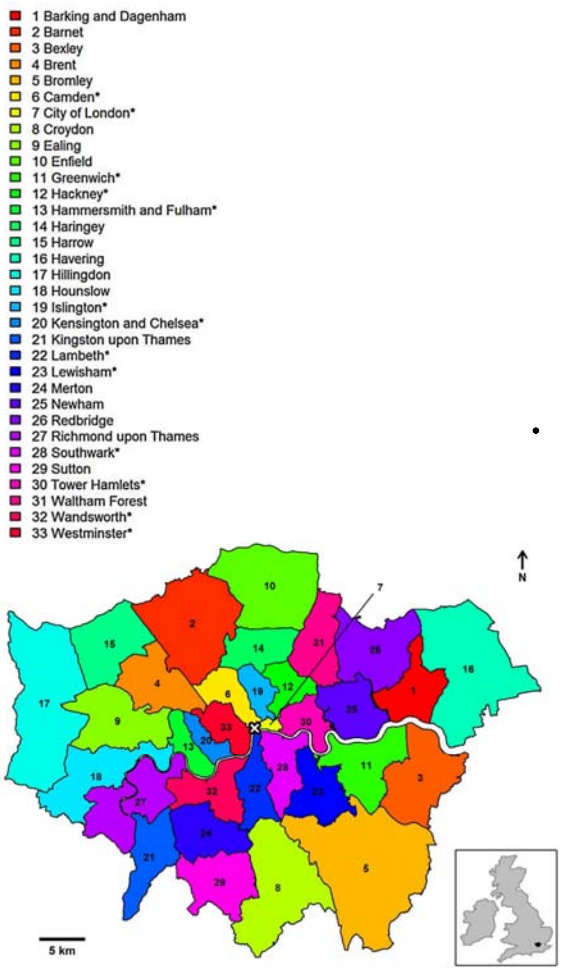
Sun et al. (2017) ERL doi:10.1088/1748-9326/aa922a

# To provide solutions need to link surface properties to processes

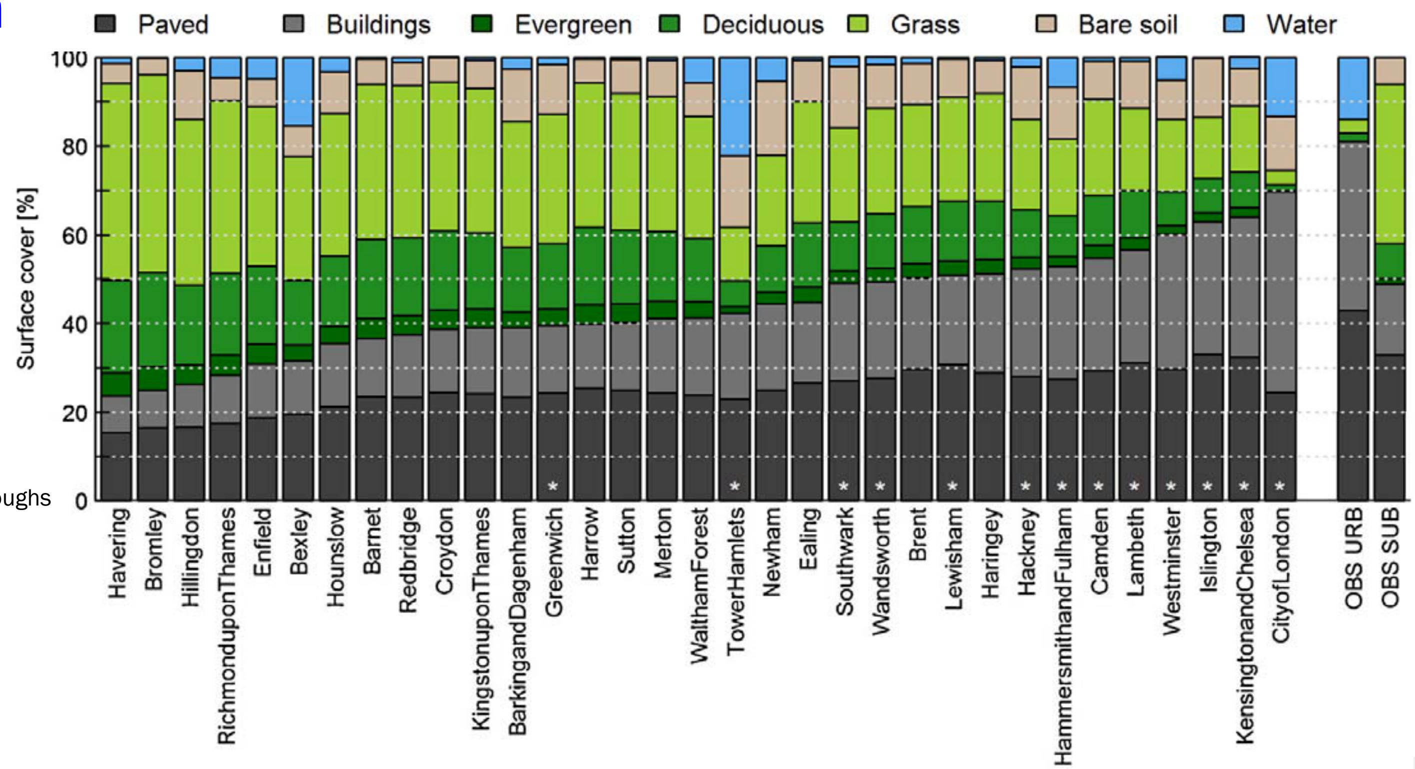



Ward & Grimmond 2017: *Landscape and Urban Planning*

# Surface cover by borough




- Inner boroughs




**Havering**
24% built
70% veg

**Increasing built fraction (Paved + Buildings)**

**City of London**
70% built
5% veg

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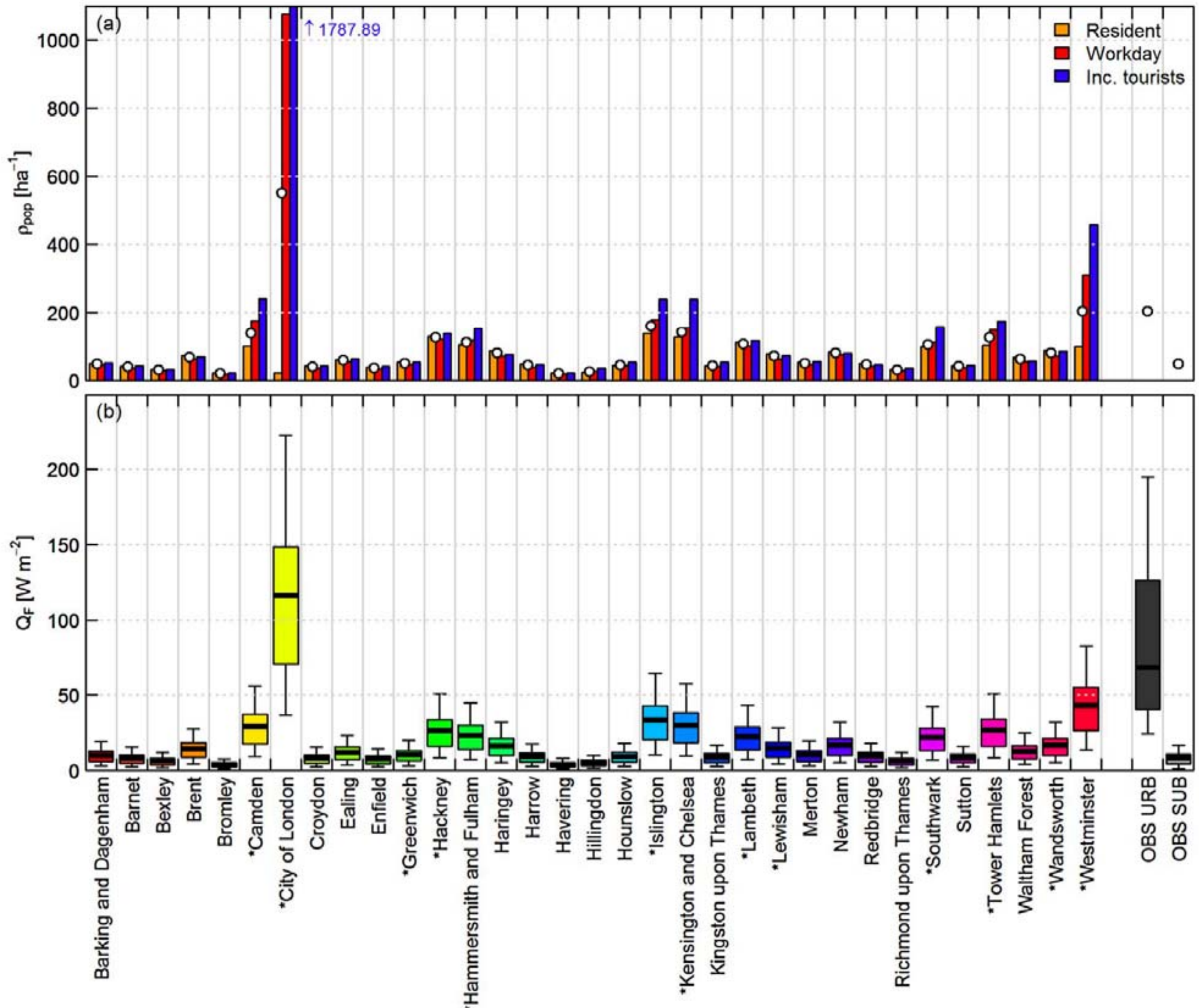
*Ward and Grimmond 2017 LUP*

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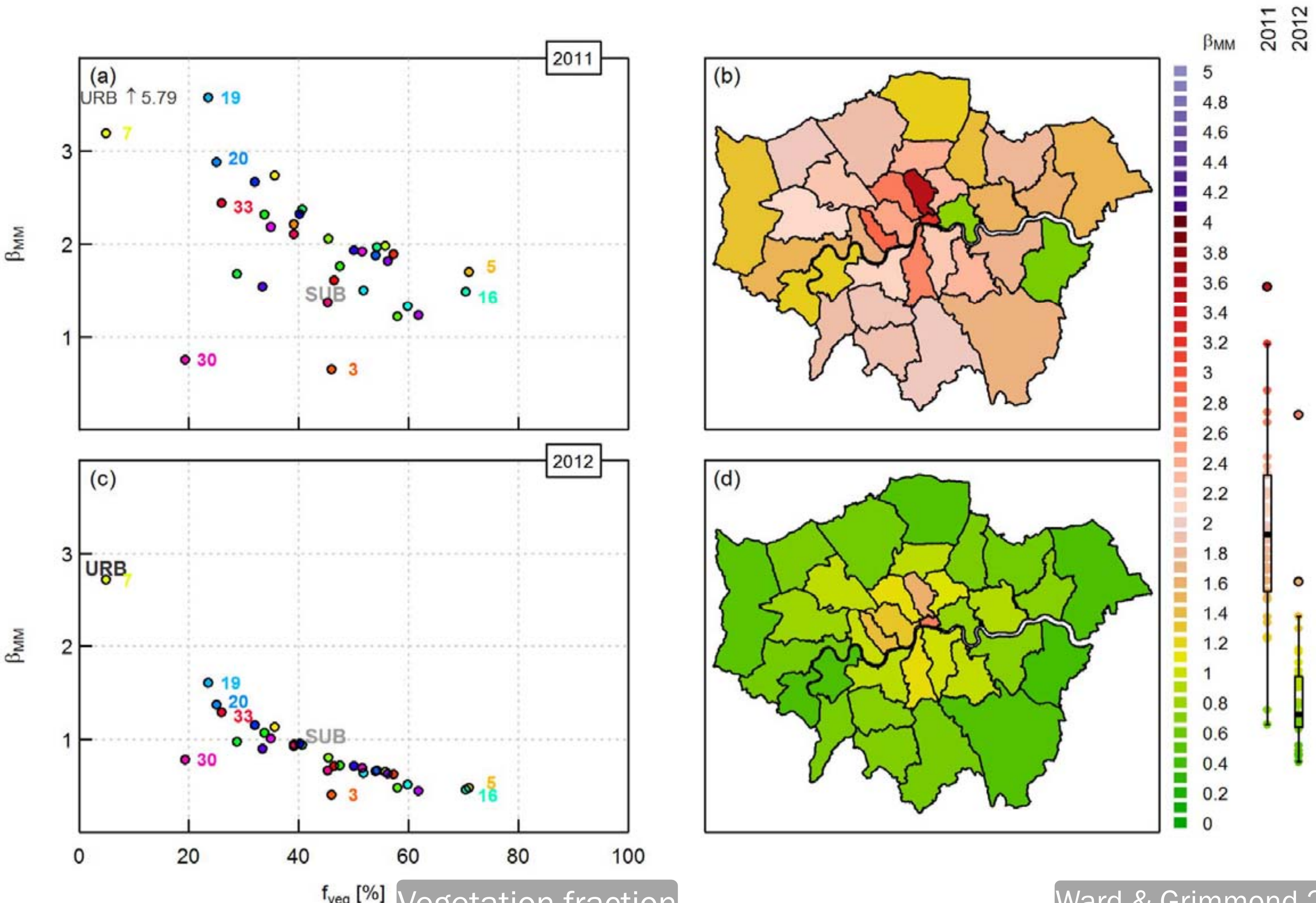
# July: SUEWS model and observations (URB: KCL; SUB: Swindon)

Median midday Bowen ratio $\beta_{MM}$




Vegetation fraction

Ward & Grimmond 2017: *LUP*

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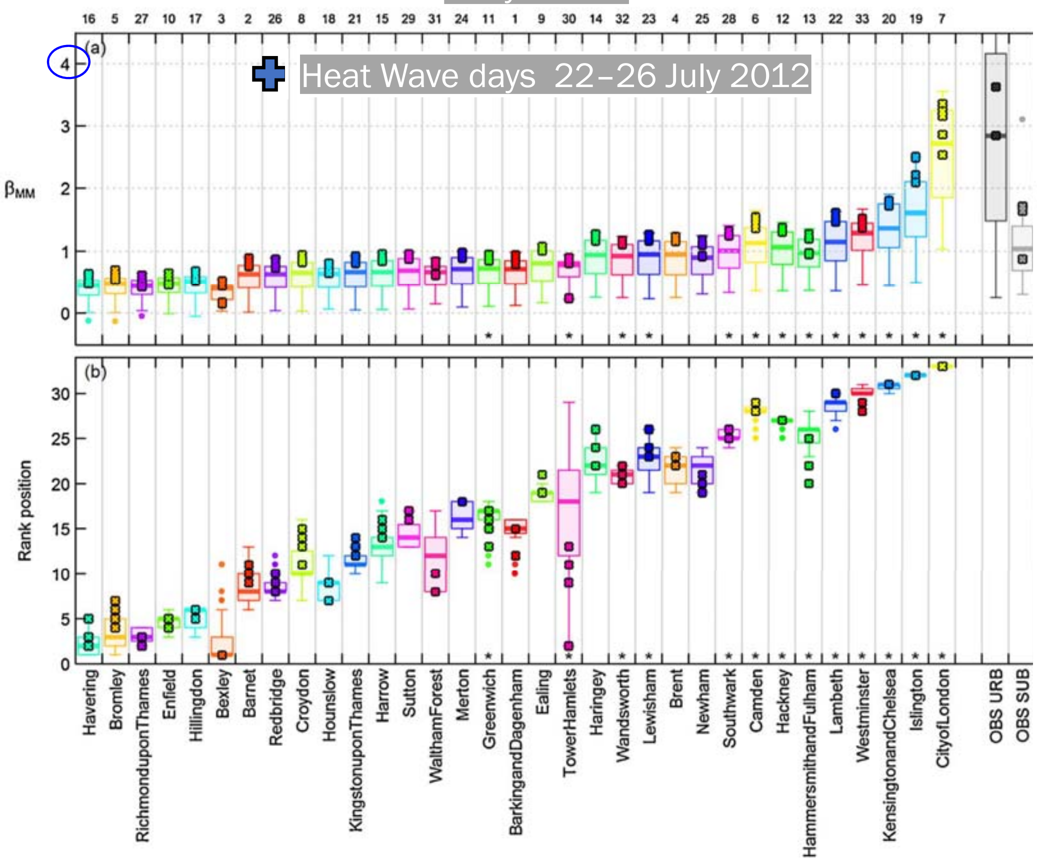
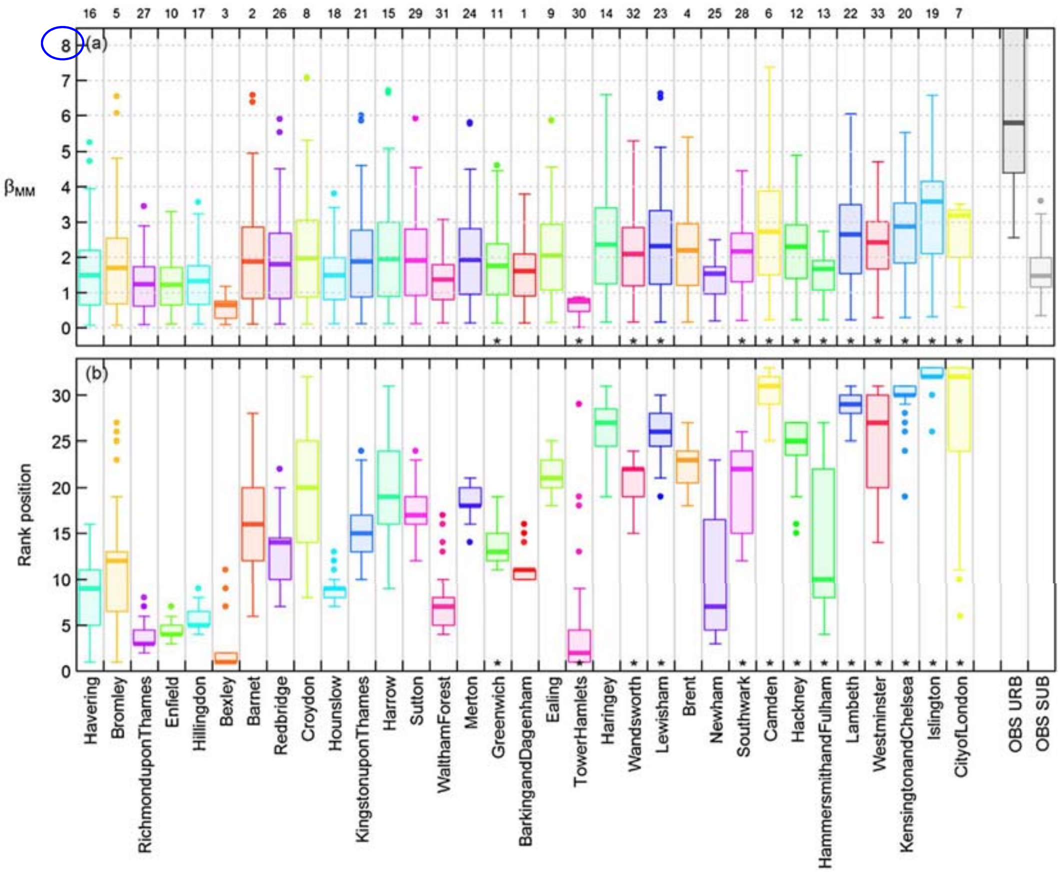
# Median midday Bowen ratio $\beta_{MM}$

July 2012




July 2011

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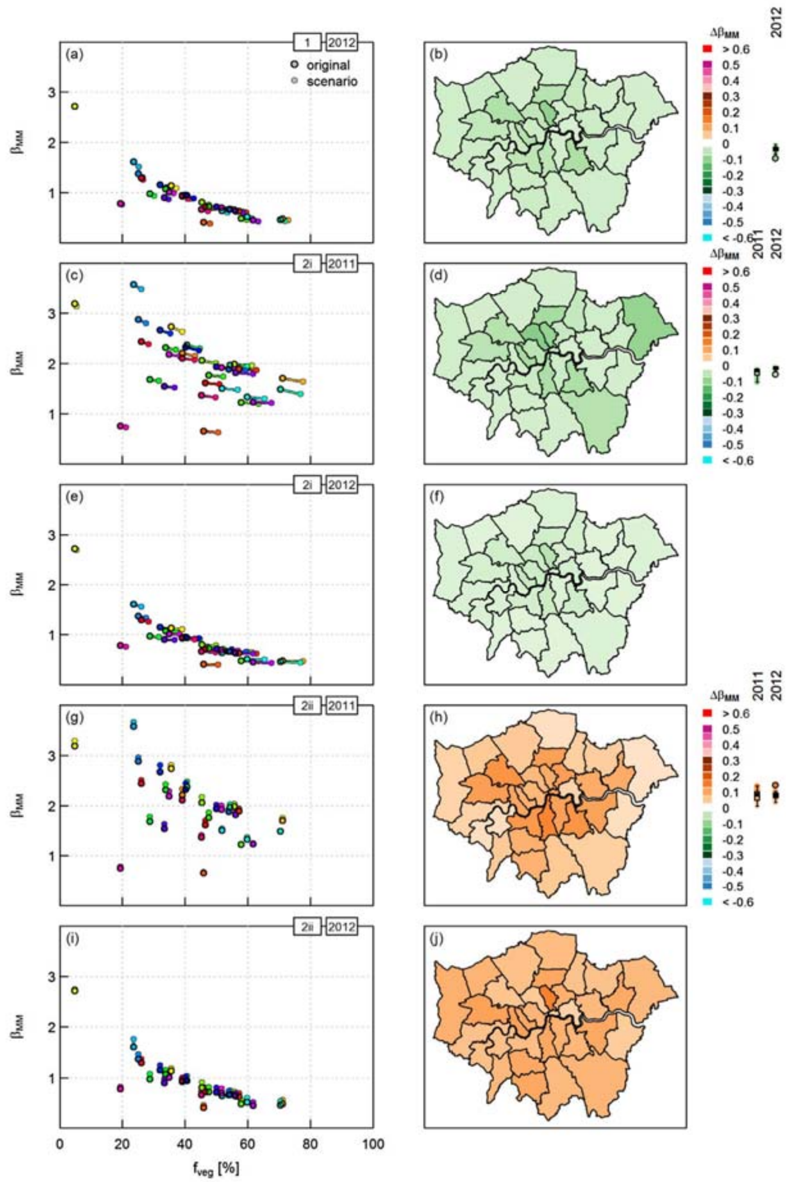
Ward & Grimmond 2017: *LUP*




**Scenario** 1

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

Scenario 2i - Increase tree cover by +25%

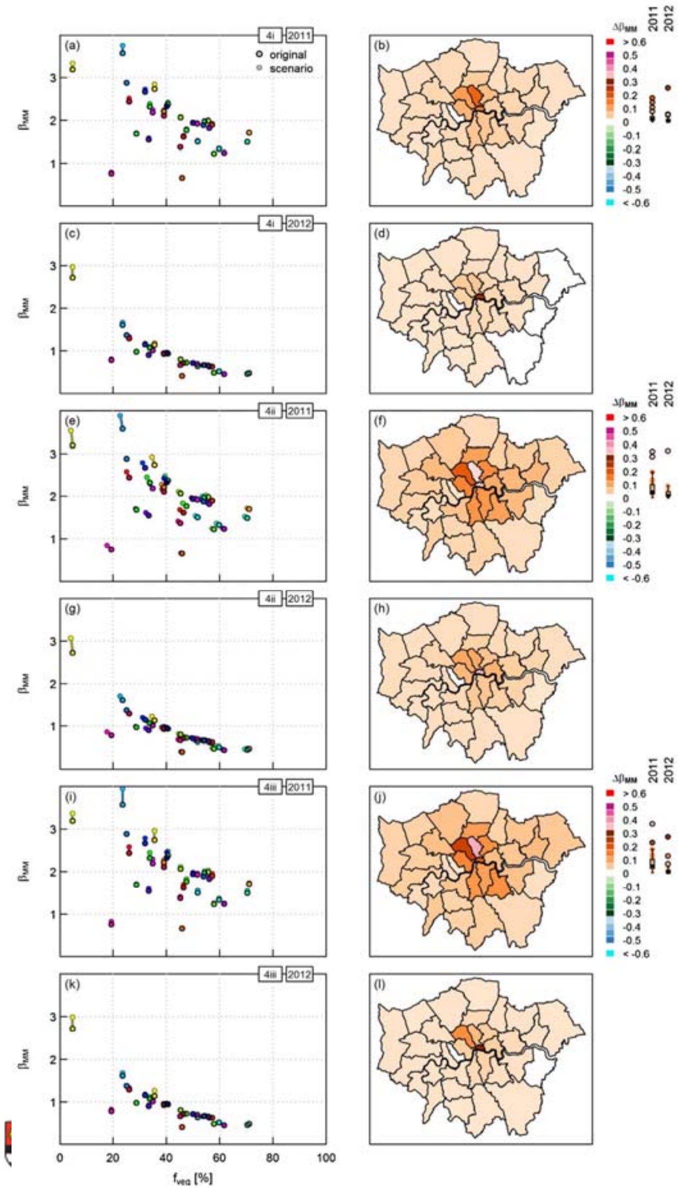
Replacing paved surfaces

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

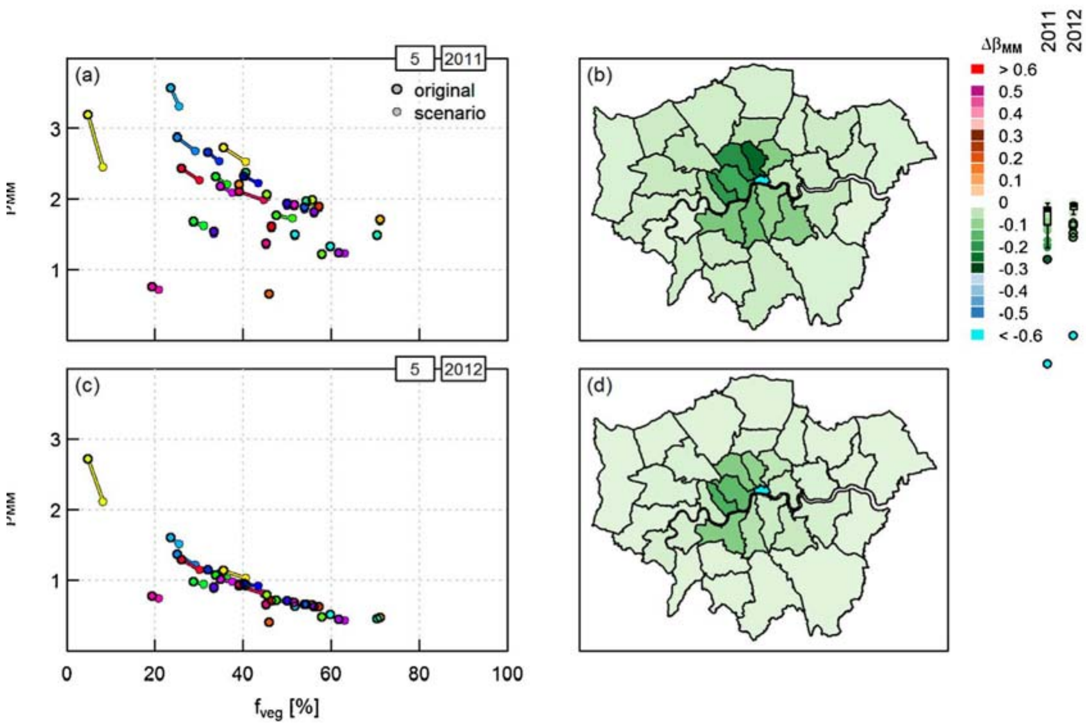
2012

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

2011

2012

Ward & Grimmond 2017: *LUP*



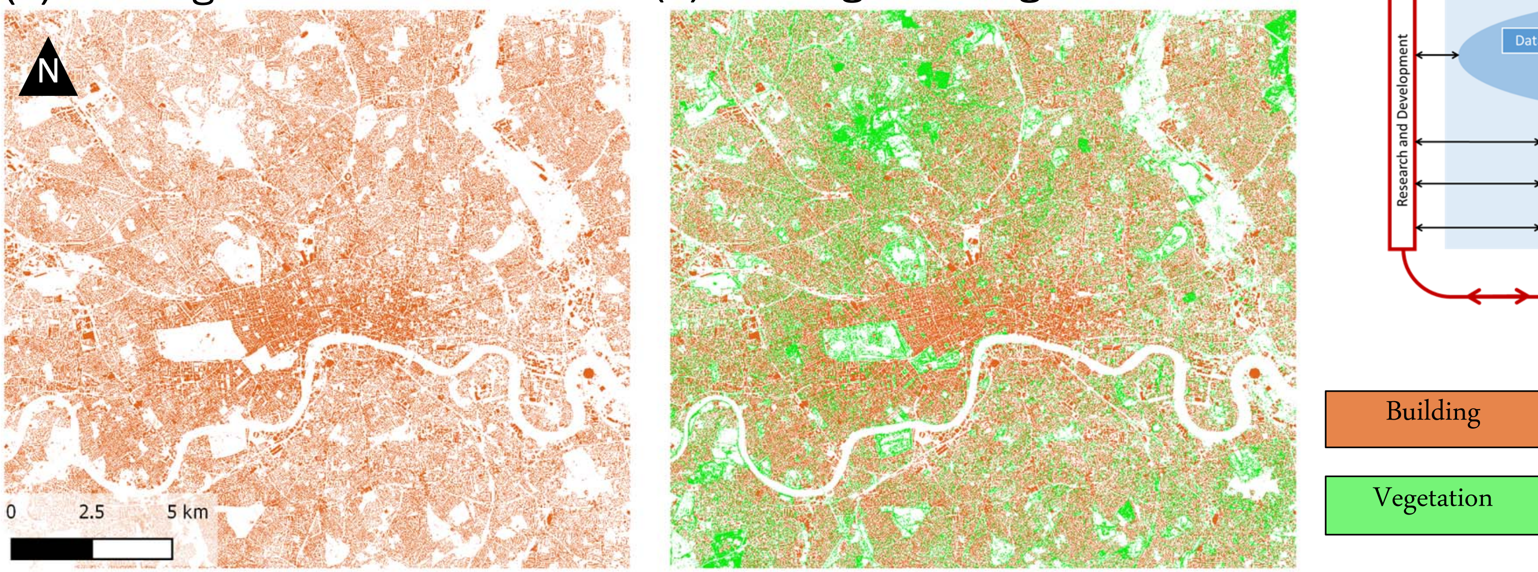

Scenario 5: **Climate-sensitive adaptation**

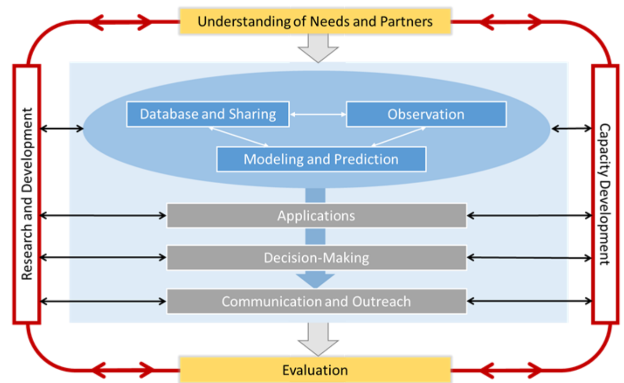
- $Q_F$ Coefficient $a_{F0}$ and $a_{F2}$ adjusted to reflect ↓ 20% building energy use
- Coefficient $a_{F0}$ adjusted to reflect reduced ↓ 10% vehicle energy use
- Tree cover ↑ 25% - reduction in paved surfaces for inner boroughs
- 25% of bare soil surfaces changed to grass for wealthy boroughs

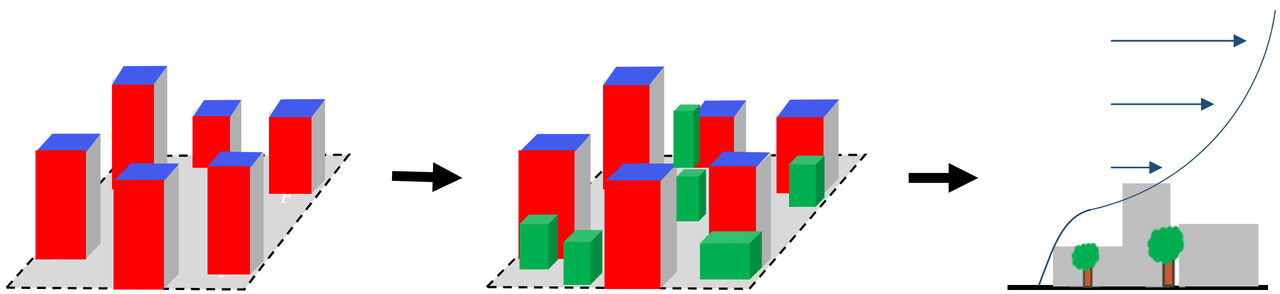
# Model parameters also need to account for both buildings and vegetation

(a) Buildings > 2 m

(b) Buildings and vegetation > 2 m

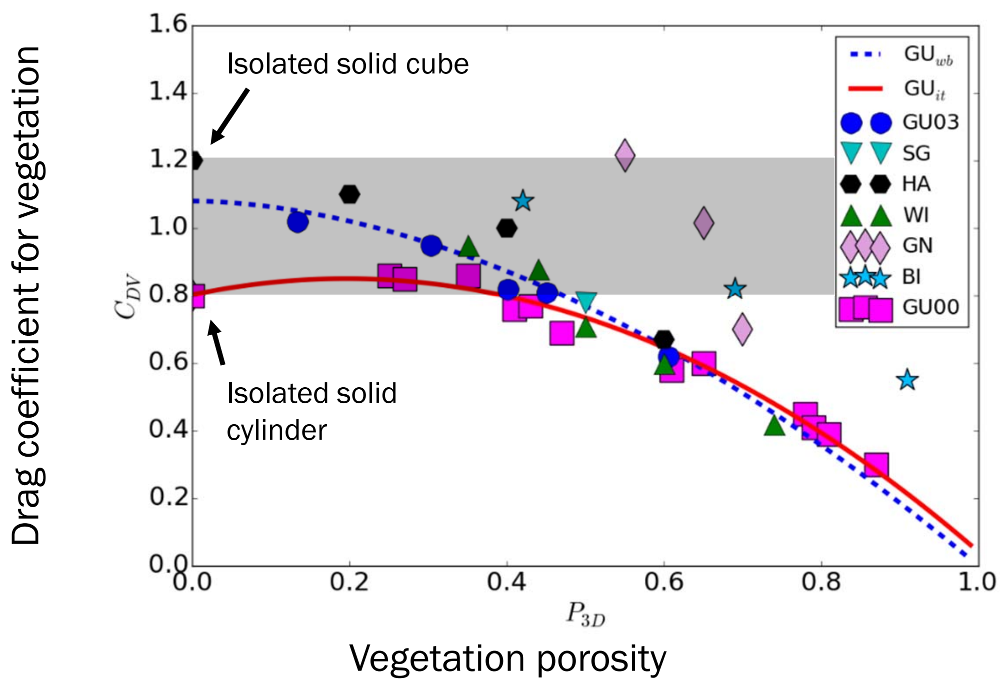


# Morphometric method development

- 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…





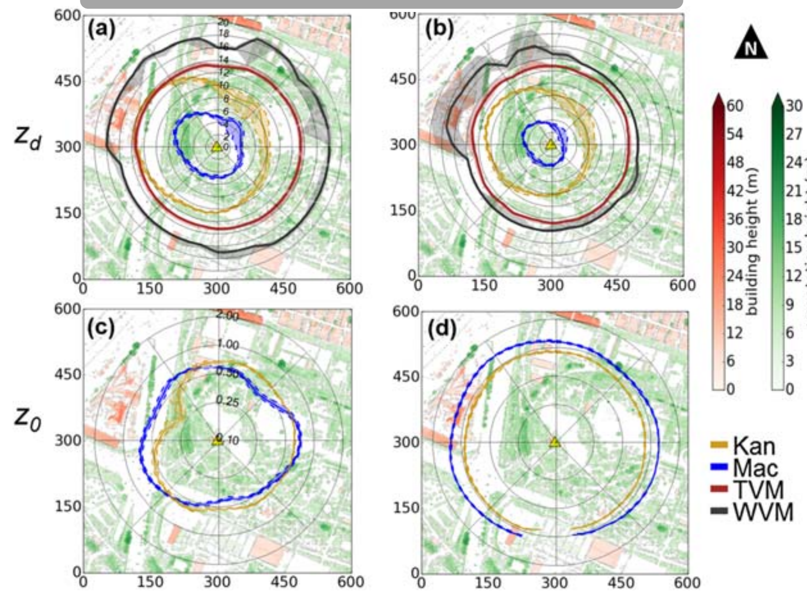

Kent et al. 2017: Aerodynamic roughness parameters in cities: inclusion of vegetation. JWEIA 169: 168-176 10.1016/j.jweia.2017.07.016

# Vegetation: impacts parameters

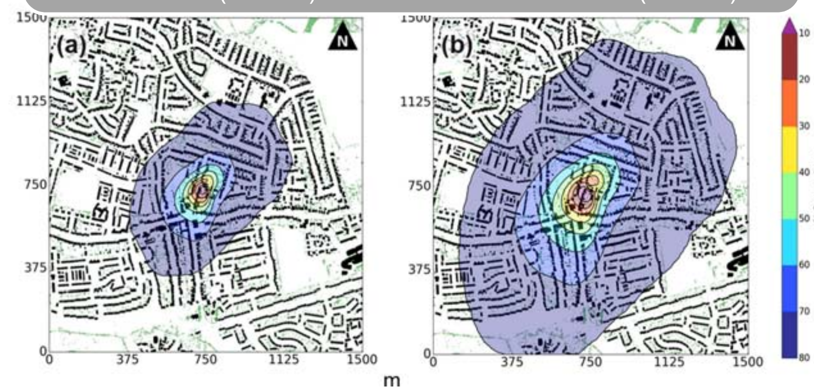
- Obvious signal of vegetation ($z_d$, $z_0$, $\overline{U}_z$)
- Directional variability and seasonal signal
- Improved wind speed estimation


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)



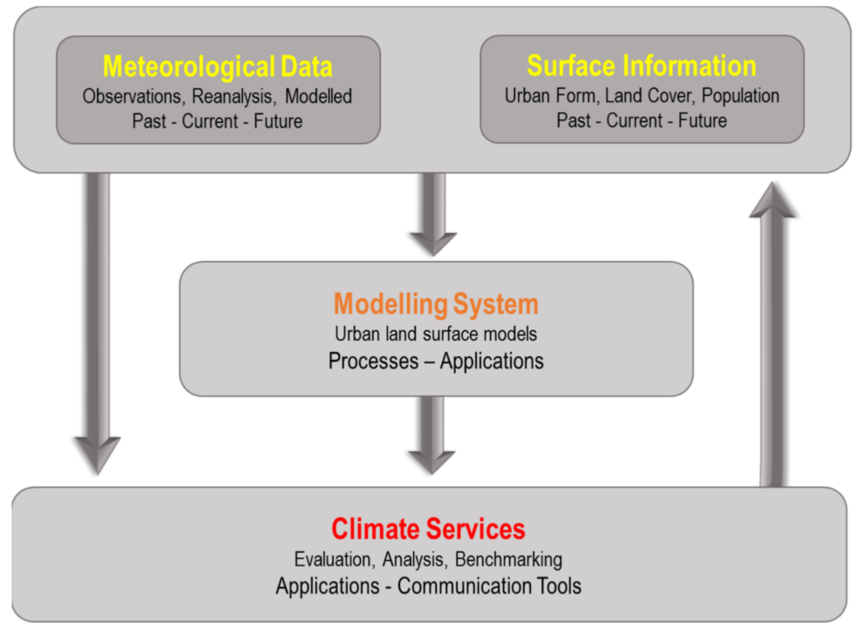



Kent et al. 2018 **Urban Ecosystems** 10.1007/s11252-017-0710-1

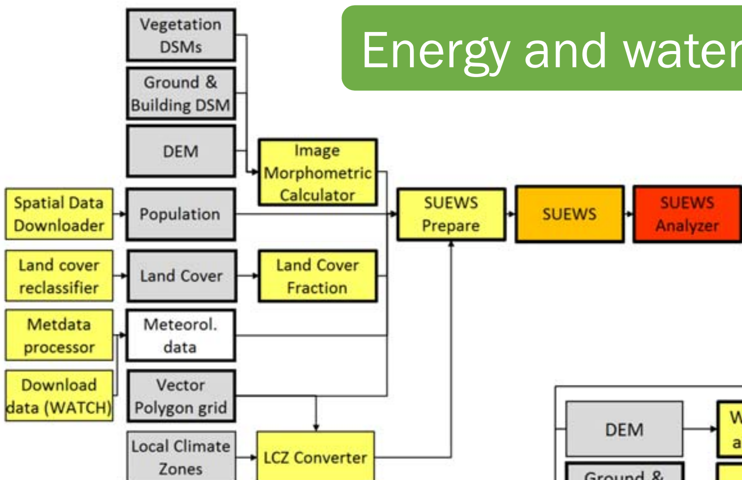
City Based Climate Service Tool

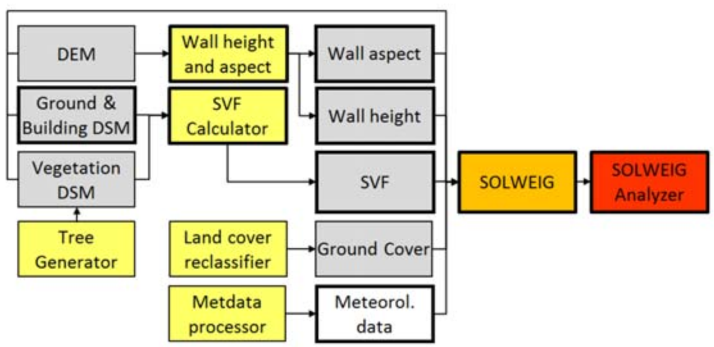
# UMEP – *Urban Multi-scale Environmental Predictor*

- 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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Lindberg et al. 2018: *Environmental Modelling and Software* 99, 70–87 10.1016/j.envsoft.2017.09.020

# 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