Finnish Meteorological Institute, 14 May 2012

KING'S College LONDON

Relevance of Vegetation to Urban Surface-Atmosphere Exchanges

Current Needs and Challenges in Urban Meteorology

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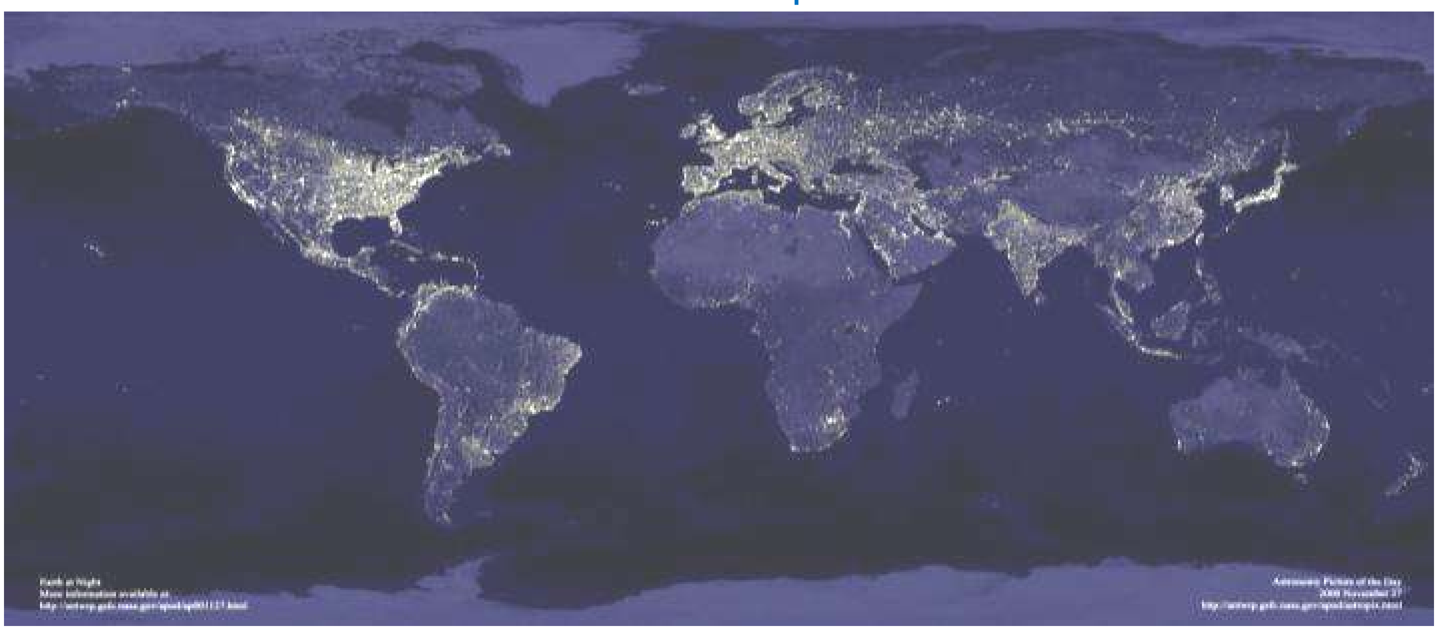


Acknowledge: All those involved in observations, Funding from UK Met Office, US NSF, EUf7 BRIDGE, EUf7 MegaPoli, NERC/ARSF, NERC ClearfLo

Land Cover Change & Urban Areas

- Urban areas – cover only ~ 2 % land surface
  - But have > 50 % of the population & are the areas of expected growth
  - High vulnerability
- Land cover change associated with them **very variable** and drives many other changes
  - Desert - Irrigated Agriculture - Urban
    e.g. Phoenix, Arizona
  - Grassland – Urban
- General assumption of decrease in vegetation, not all ways
  - can be more trees in urban areas than the surrounding area
    - Urban Forest
- Increase in impervious surfaces

Changing View of Cities

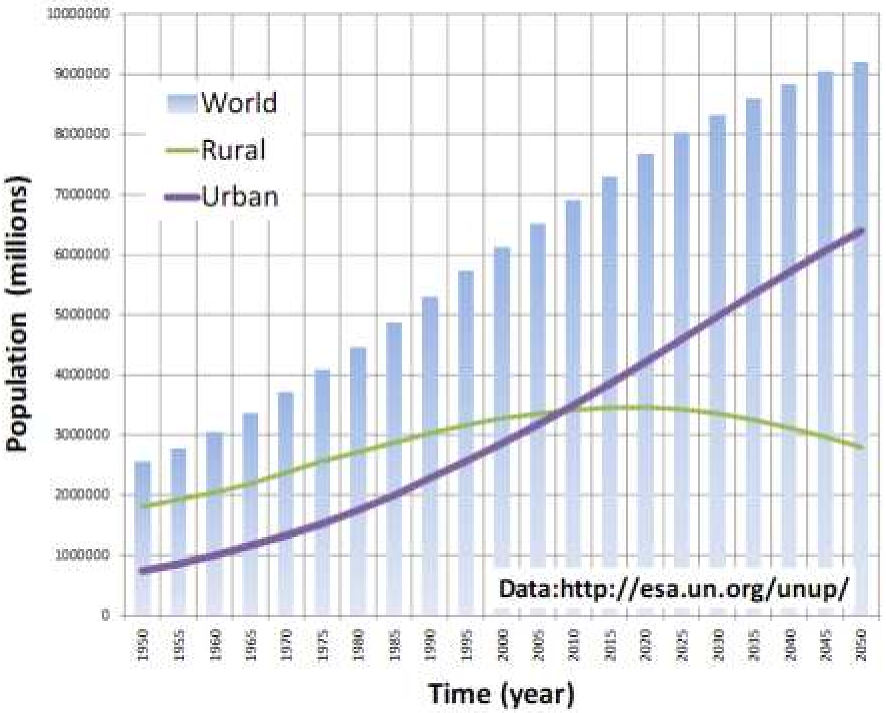
- 1820's
  - Warmth of urban areas first measured (Luke Howard)

http://www.rmets.org/weather/observing/luke-howard.php

- 1970-1980's
  - First Urban Energy Balance (UEB) measurements
  - First Urban Land Surface Models (LSM)
- 1990's
  - Number of short term observation campaigns (e.g. periods in summer)
- 2000's
  - Annual (or longer) UEB observations
  - First urban CO_2 flux observations
  - Development of large number of Urban LSM

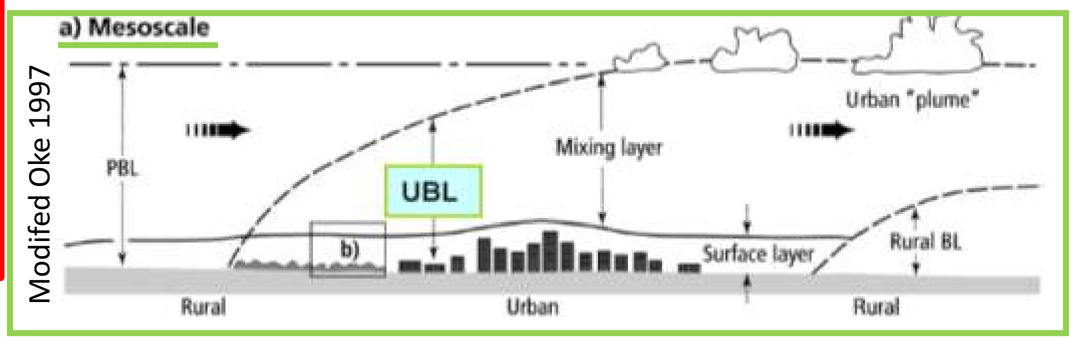
Changing view of cities

- Increasing **number** of people
- Increasing **densities** of people
- Scale resolved increased (increased computing capacity, wireless sensors)

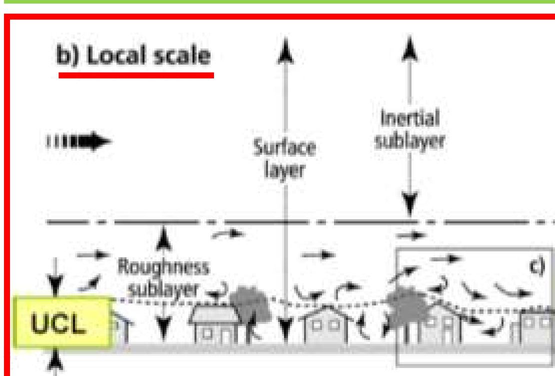


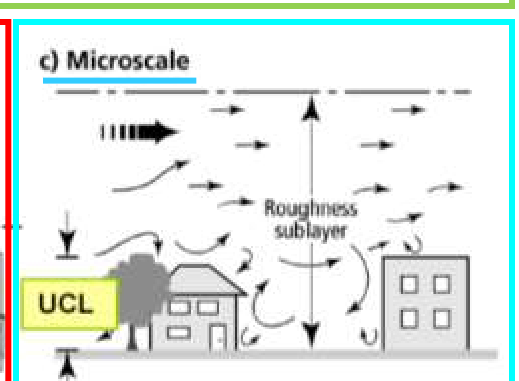
- Applications
  - **Micro-scale**
    - Human comfort, Building design, Green infrastructure, Construction, Renewable energy installation and operations
  - **Local-scale/Neighbourhood**
    - Flood control, thermal comfort, mitigation strategies, energy demand
  - **Meso-scale/City - wide**
    - Forecasting, air quality applications, place most vulnerable at risk to climate change,

Scales



Gothenburg

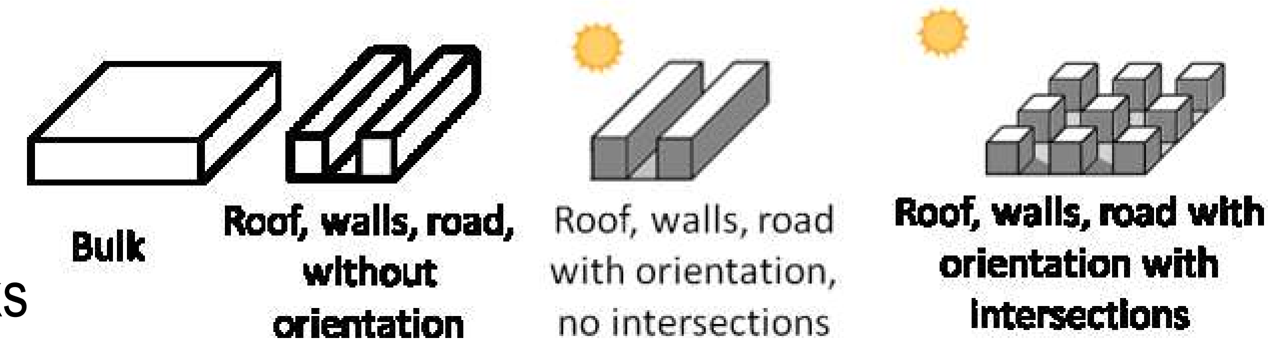


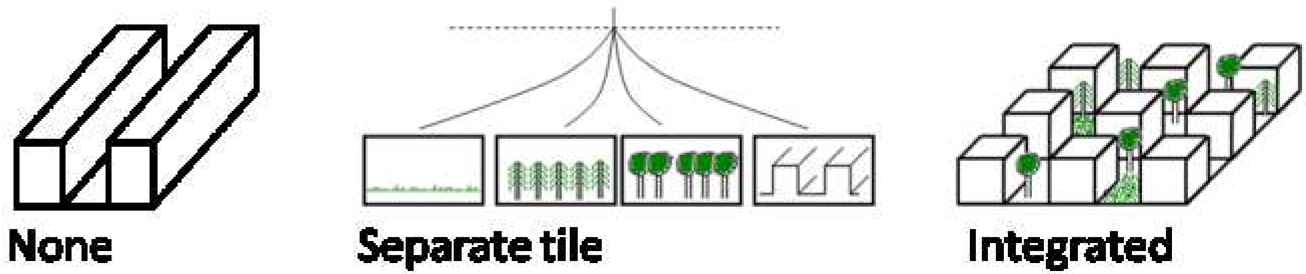


Chicago

Changing View of Cities

- Urban Surface – Atmosphere Exchanges
  - Concrete
  - Canyons
  - Cubes
  - Varying sizes blocks
  - Vegetation

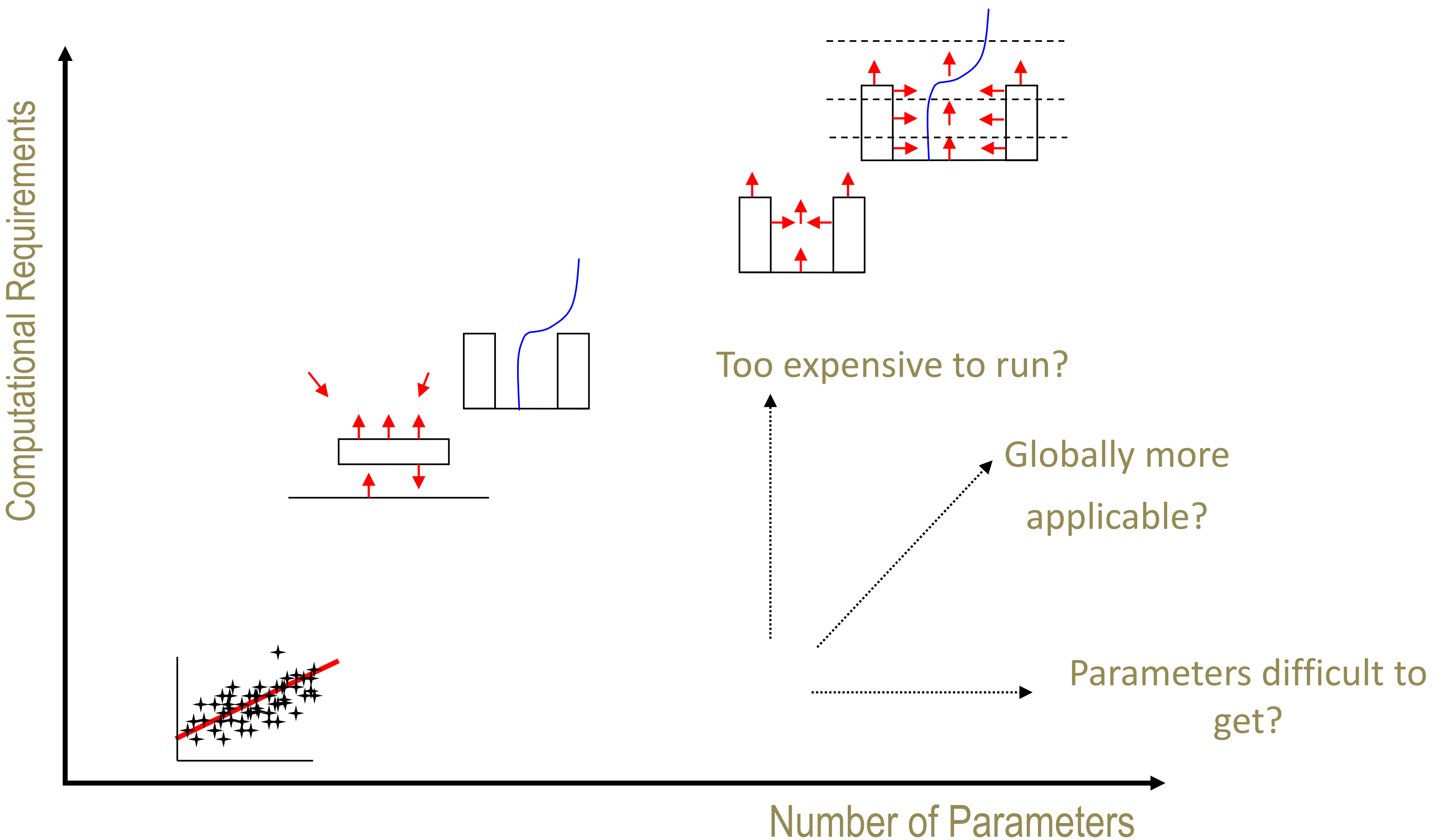




Grimmond et al. 2010 JAMC
2011 IJC

- Increasing model resolution
  - How complex do the models need to be?
  - How many classes do we need for urban areas?

Complexity of Urban Land Surface Models



M Best

Compatibility

- To evaluate models, the scale of measurements and the models need to be compatible
  - What does the model actually simulate?
  - Measurements need to meet appropriate assumptions

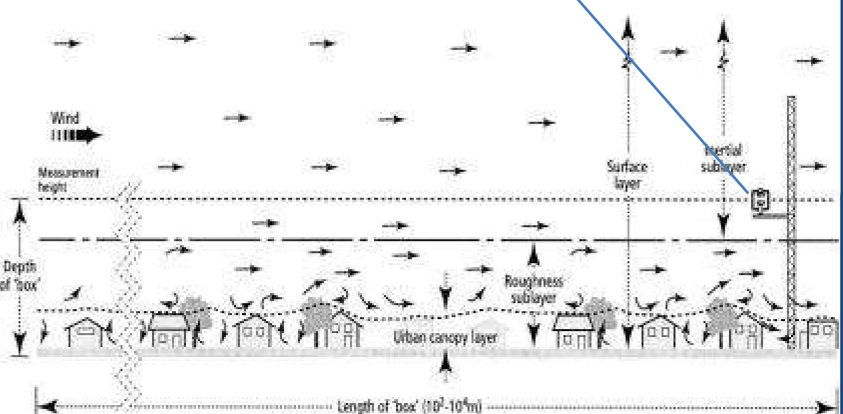
Local Scale: Land Surface Model + Observations

Forcing data for LSM – from higher level in model (e.g.meso-scale) or **observations**

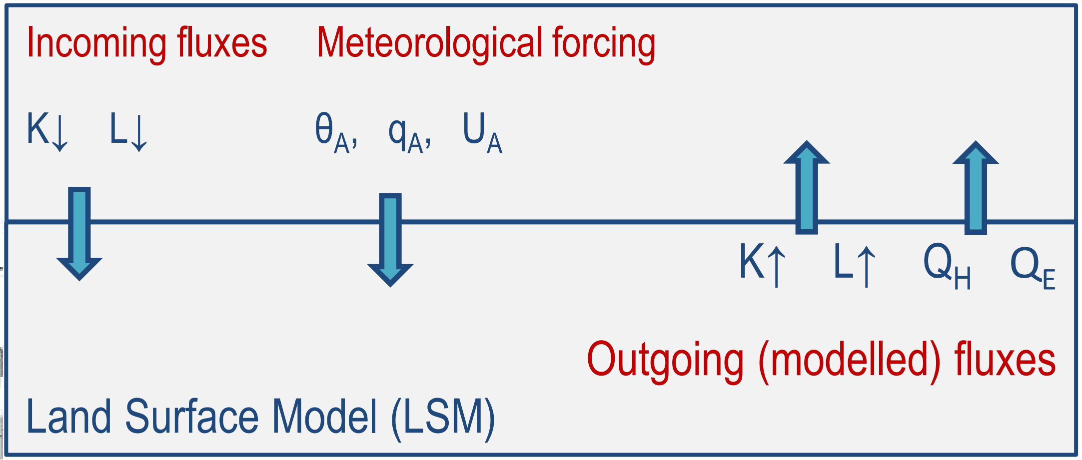
- K↓ Incoming shortwave radiation $Q\downarrow = K\downarrow + L\downarrow$
- L↓ Incoming longwave radiation
- θ_A Air temperature
- q_A Specific humidity
- U_A Wind speed

Modelled fluxes - passed to next model level

- K↑ Outgoing shortwave radiation
- L↑ Outgoing longwave radiation
- Q_H Turbulent sensible heat flux
- Q_E Turbulent latent heat flux

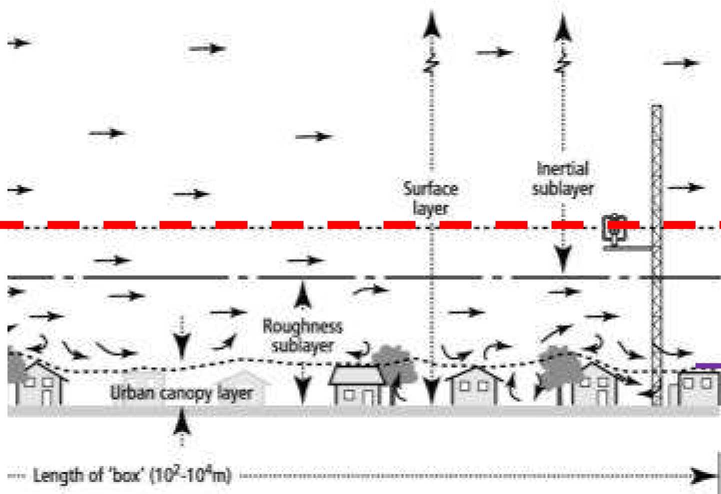


Grimmond and Oke, 2002, JAM

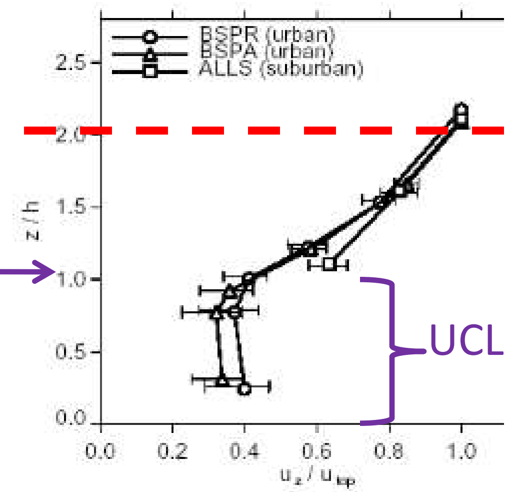


Microscale vs Local-Scale

- Function:
  - height (& variability)
  - roughness element density
  - shapes of roofs
  - stability
  - local scale variability



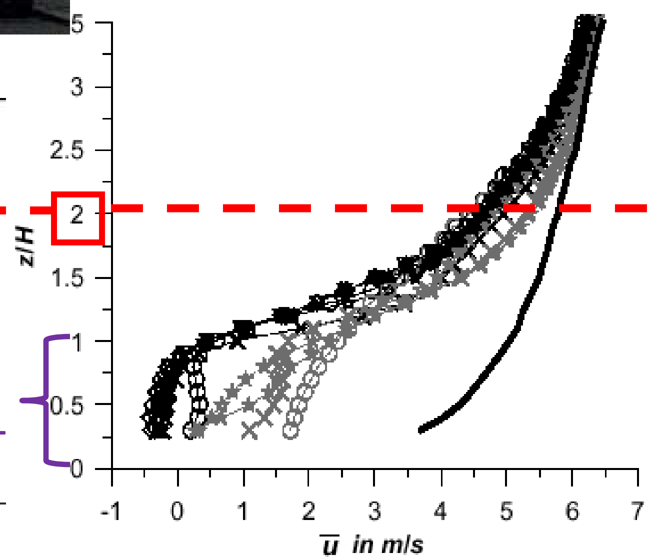
Grimmond and Oke 2002 *JAM*



Christian et al. (2003) 4th International Conference on Urban Air Quality, Prague

Real world measurements

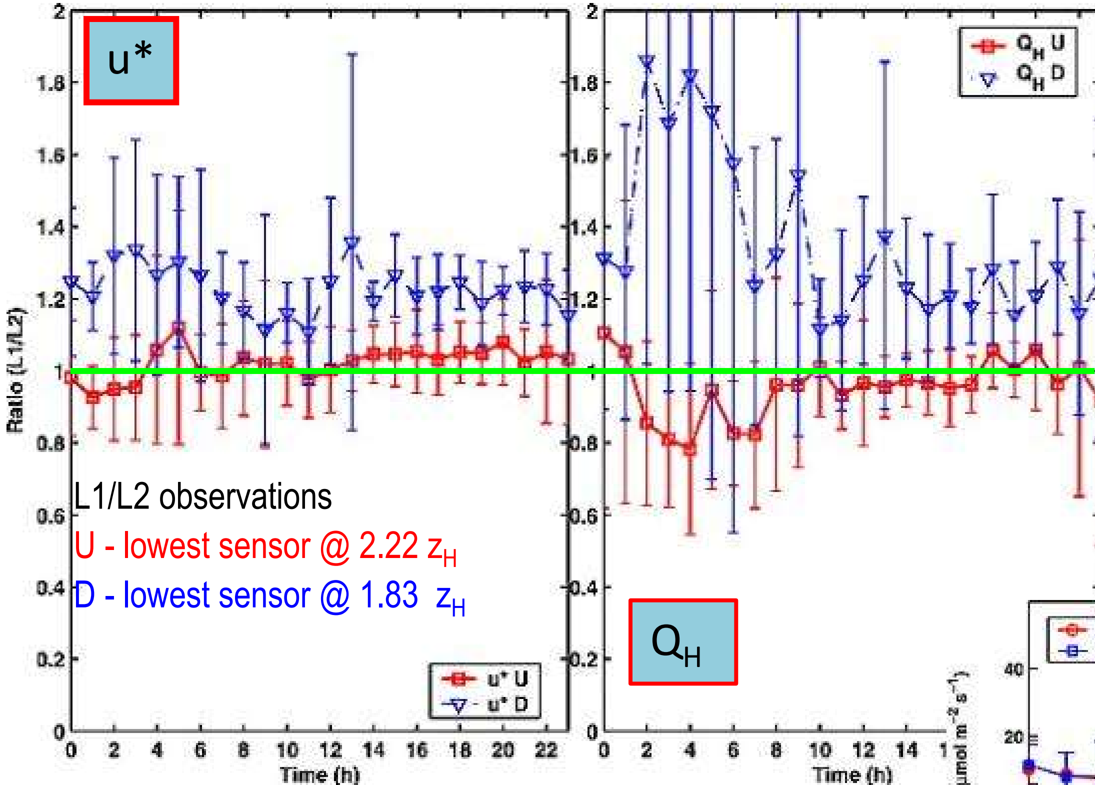
Basel



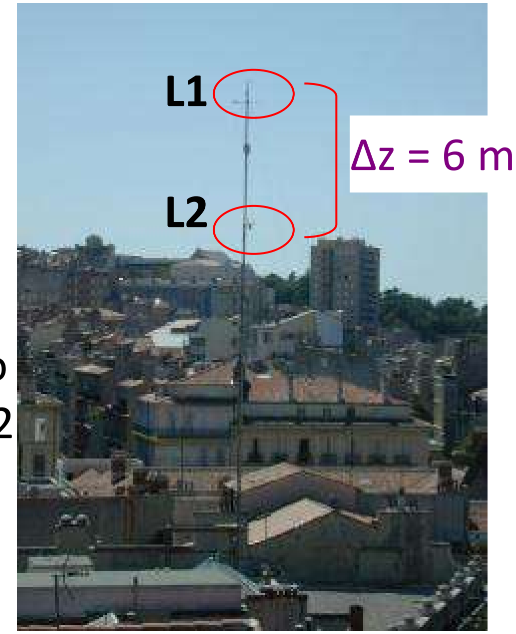
Kastner-Klein & Rotach 2004 *BLM*

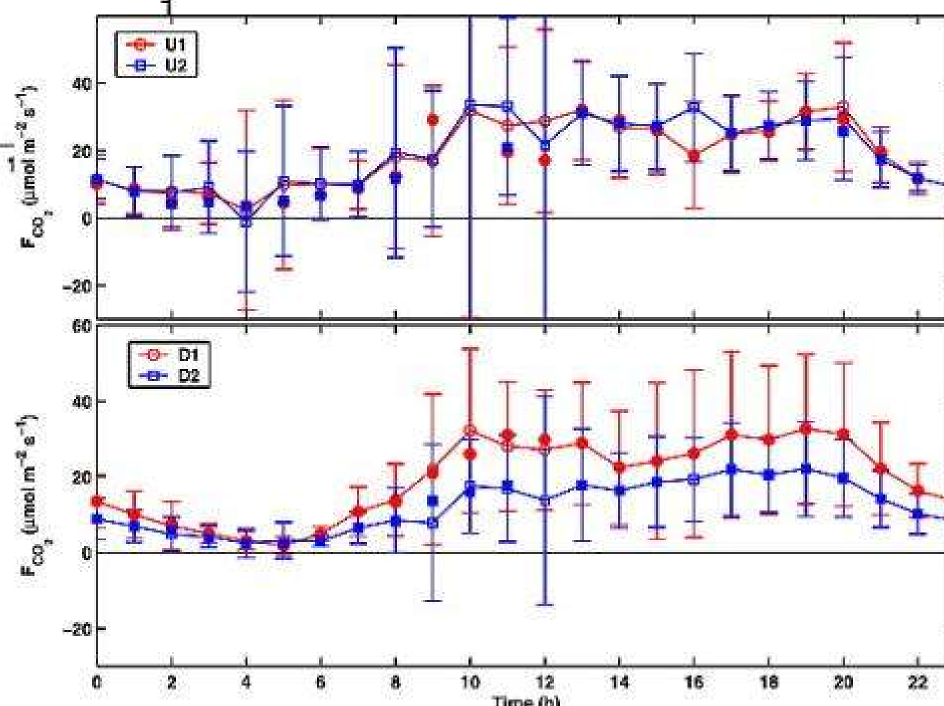
Wind tunnel observations

Impact of the Height of Observations



Ratio L1/L2



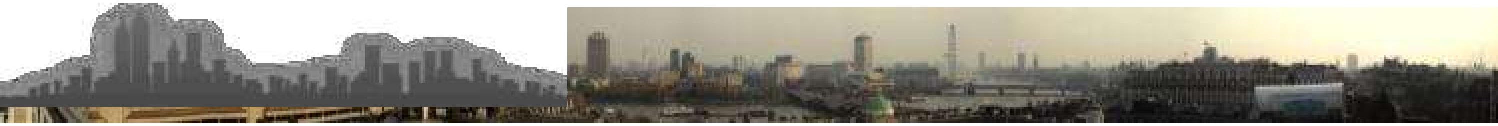


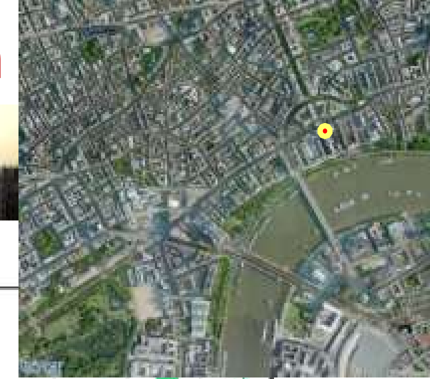
Carbon Dioxide Fluxes

@ each level

Grimmond *et al.* 2004: JGR

Central London (Eddy Covariance): Low Vegetation





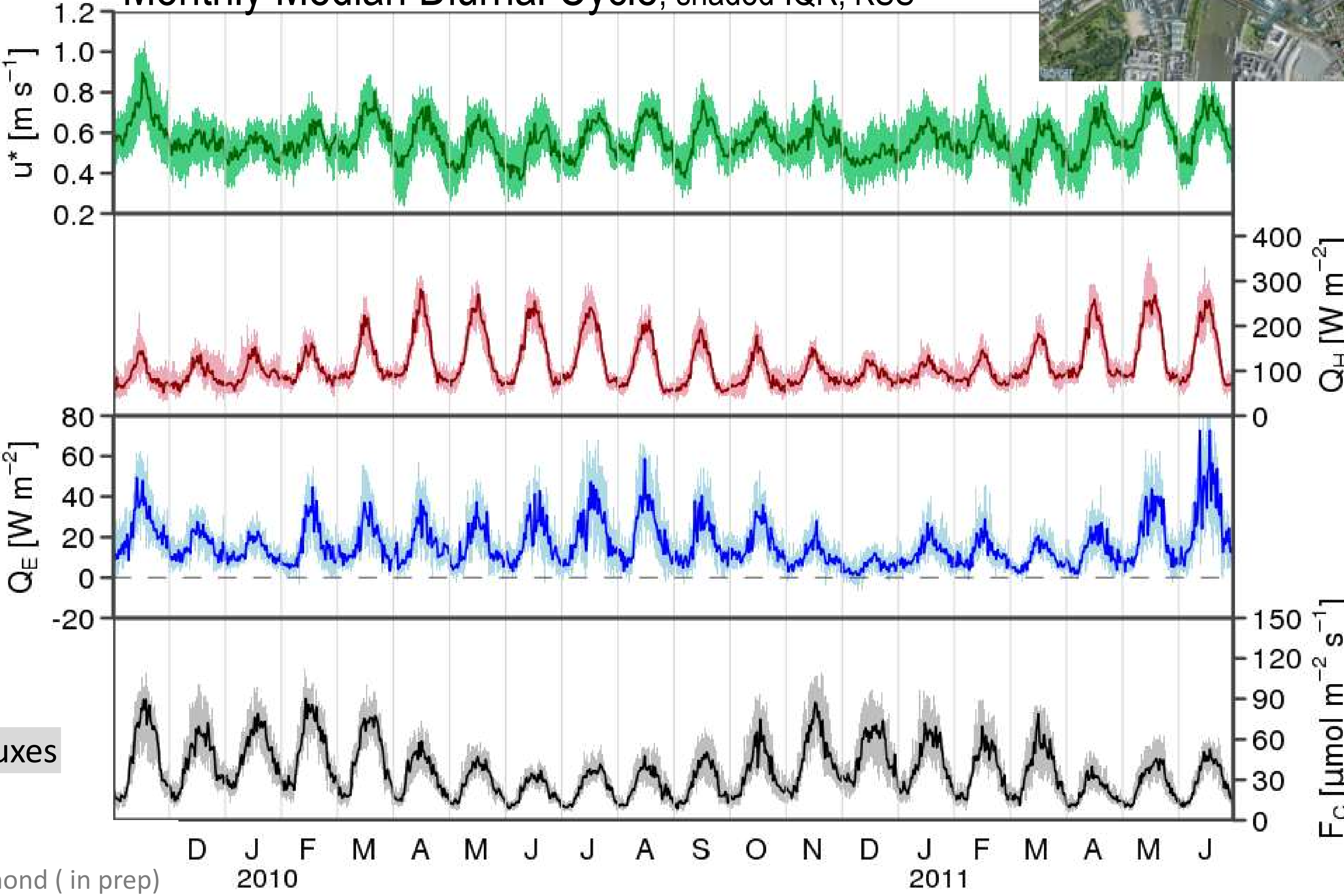
Monthly Median Diurnal Cycle, shaded IQR, KSS

u*

Q_H

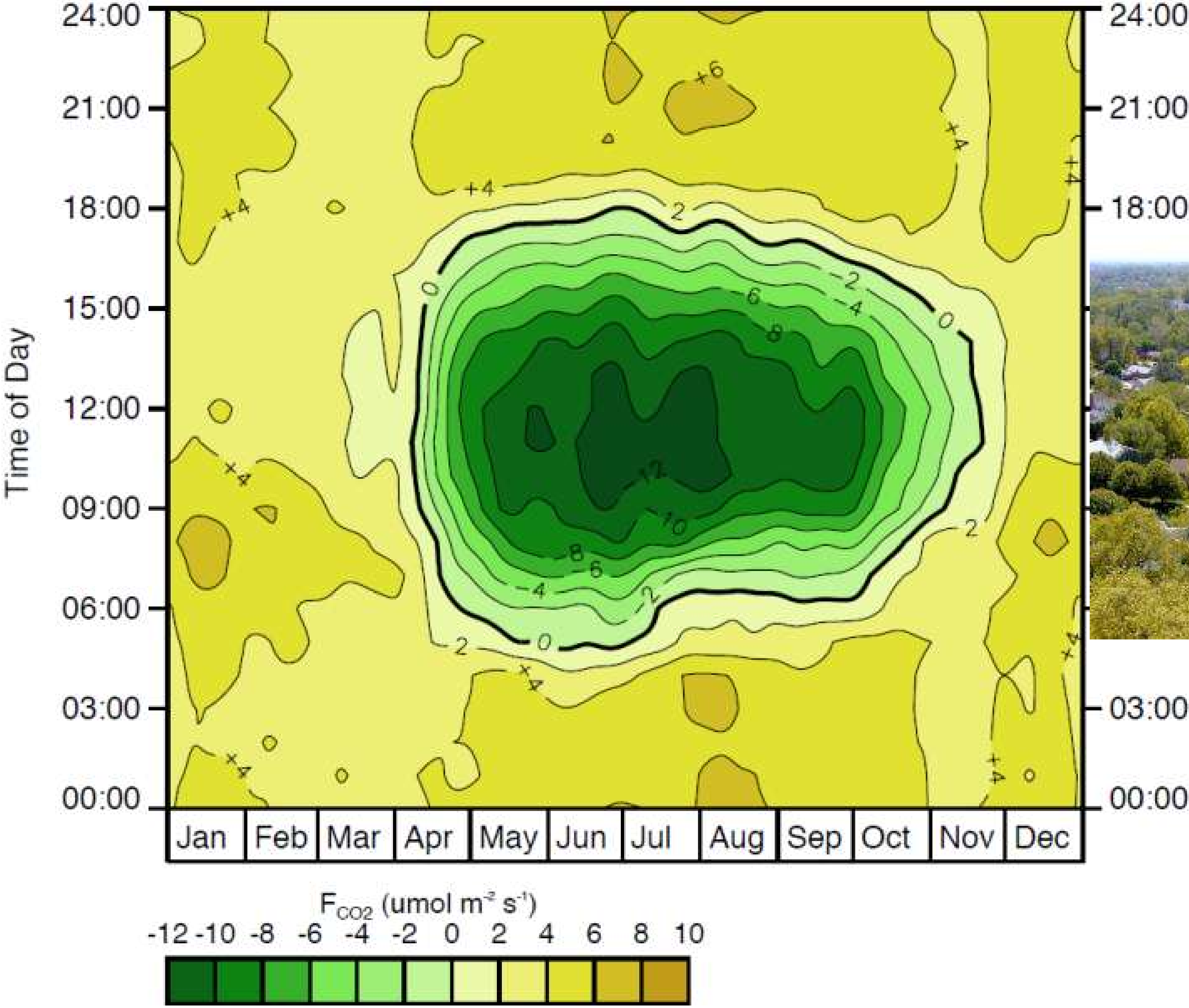
Q_E

CO_2 Fluxes



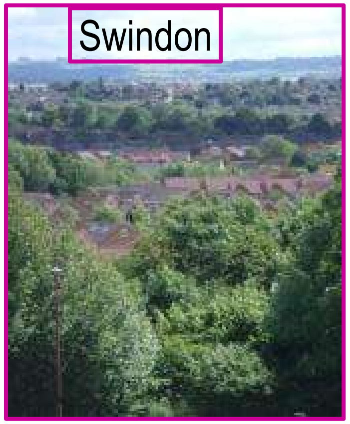
Kotthaus & Grimmond (in prep)

Suburban Baltimore Mean Hourly F_{CO2} 2002-2006



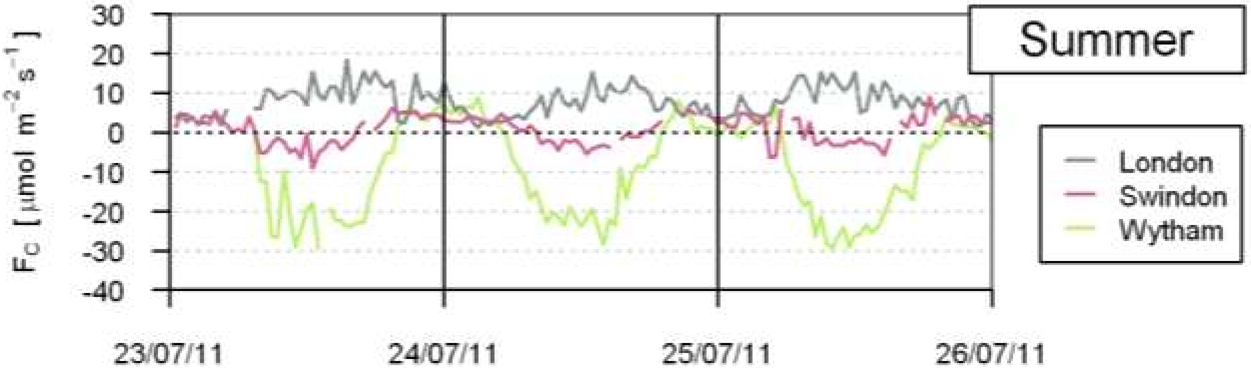
Crawford et al. (2011) AE

F_{CO2} - Urban-Suburban-Rural Comparison



Thomas et al. (2011)

- release of CO_2 increases with level of urbanisation and decrease of vegetative fraction

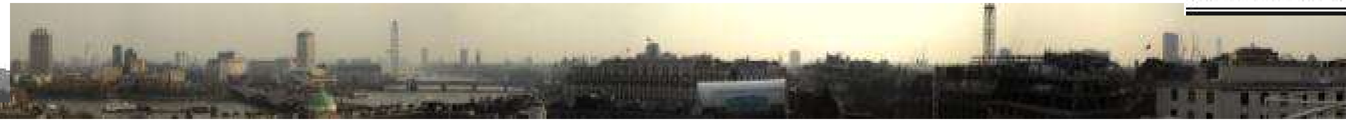


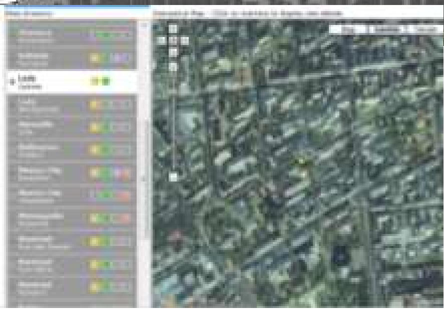
Swindon:

- small source in summer, significant uptake by vegetation
- anthropogenic contributions more important in winter

Kotthaus, Ward, Grimmond, Evans (2012)

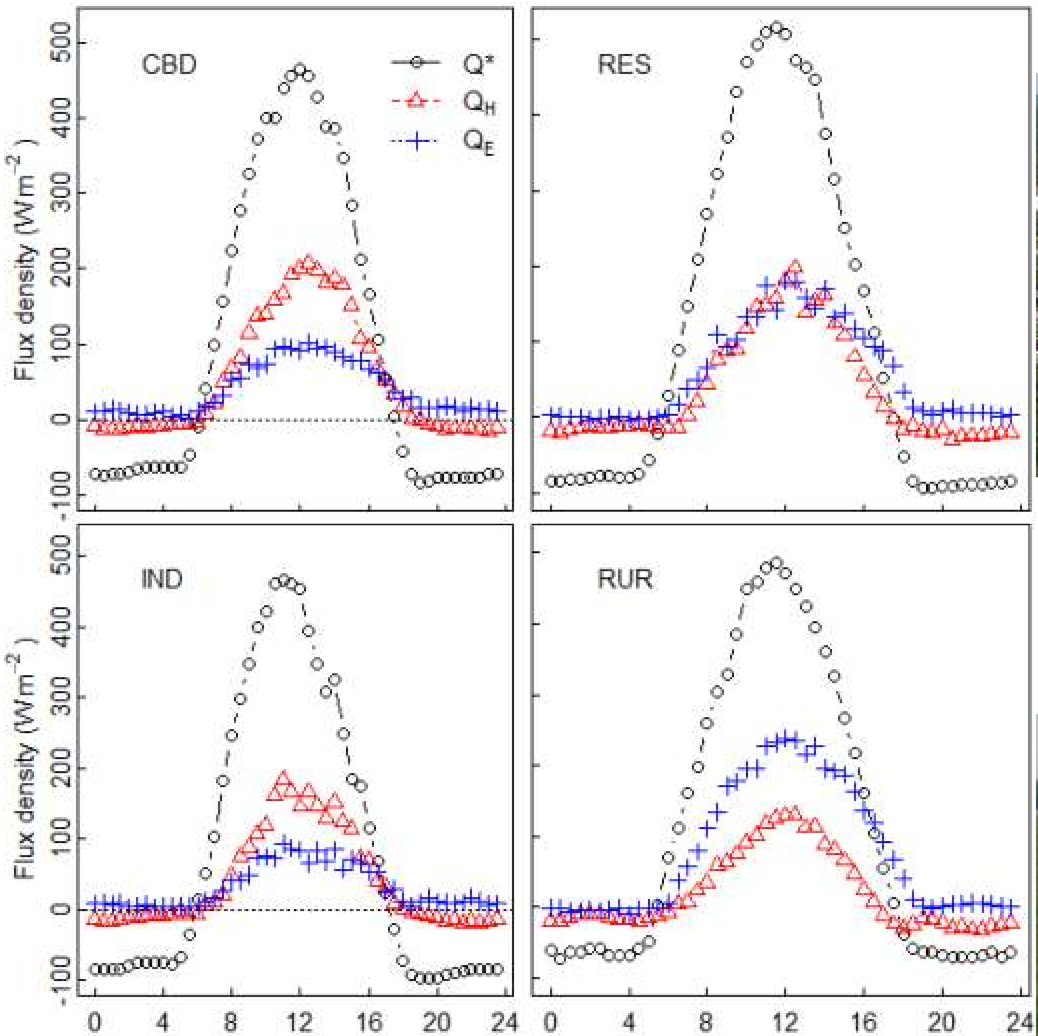
Variability Within A City: Lodz, Poland

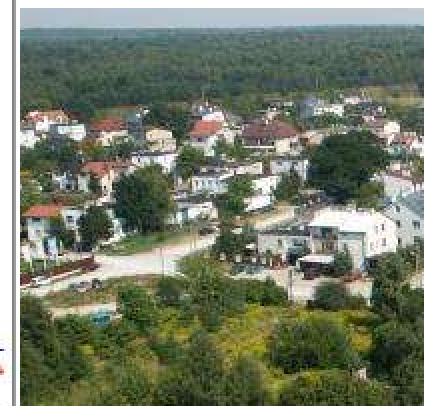




17 Aug – 2 Sept 2002

Offerle et al. 2006 JAMC

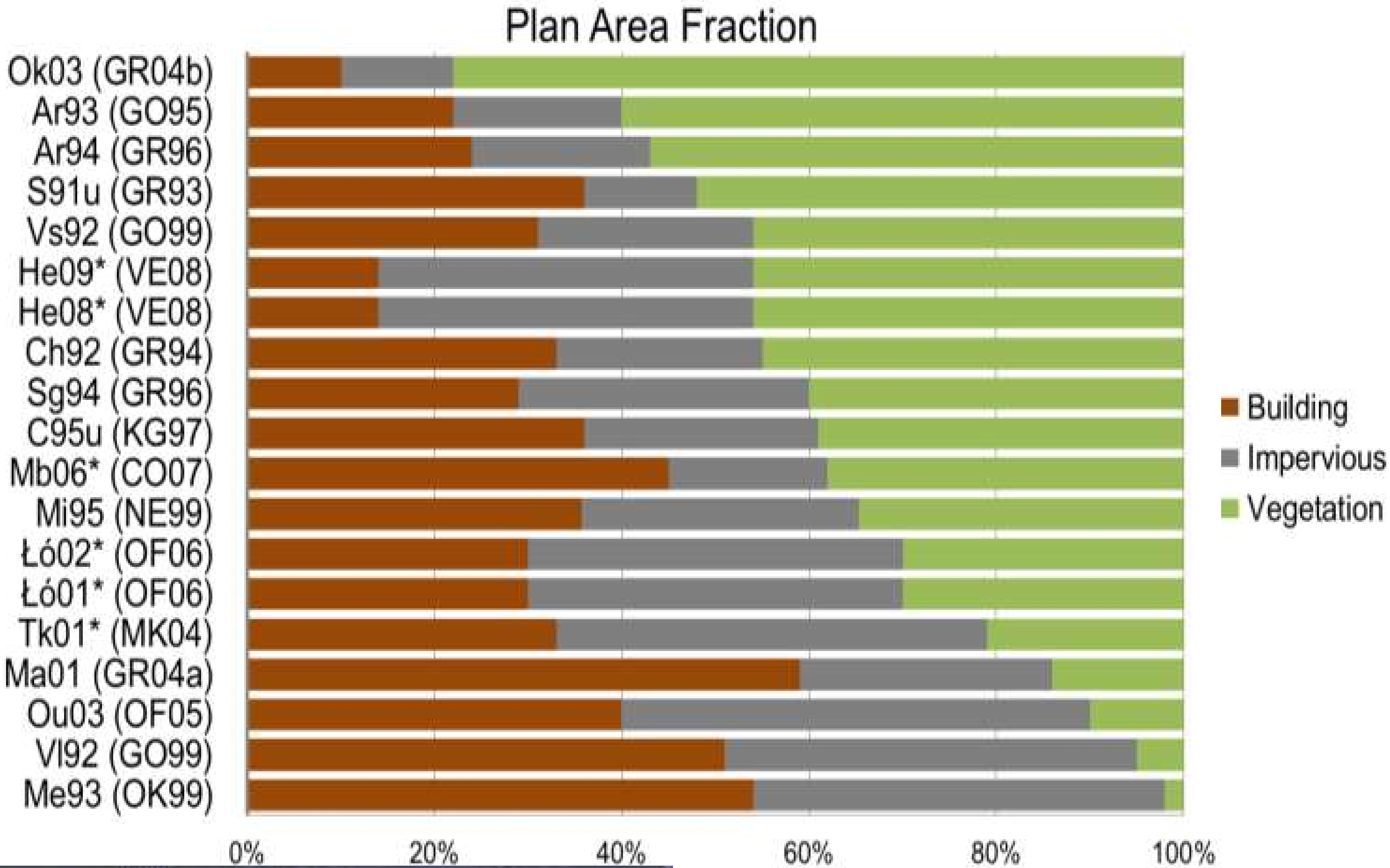




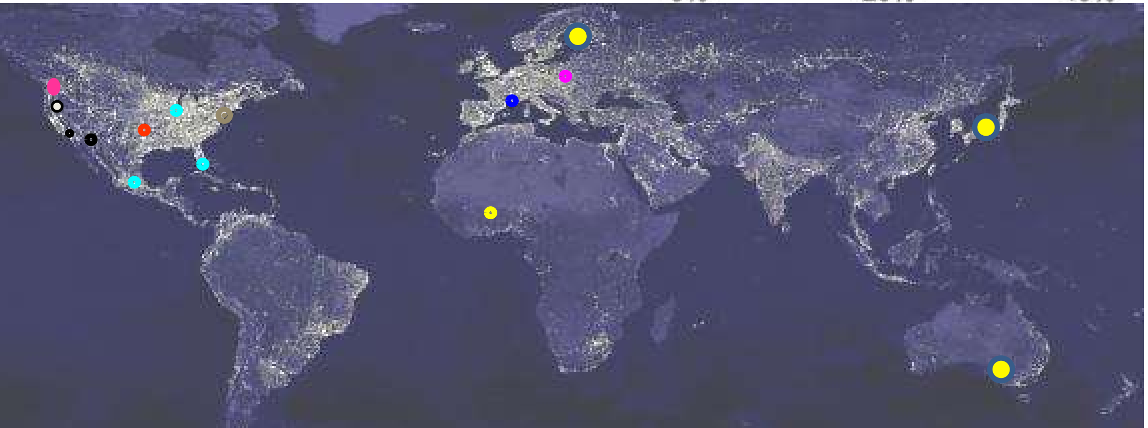
Large number of observations of urban energy balance fluxes

Site (reference)

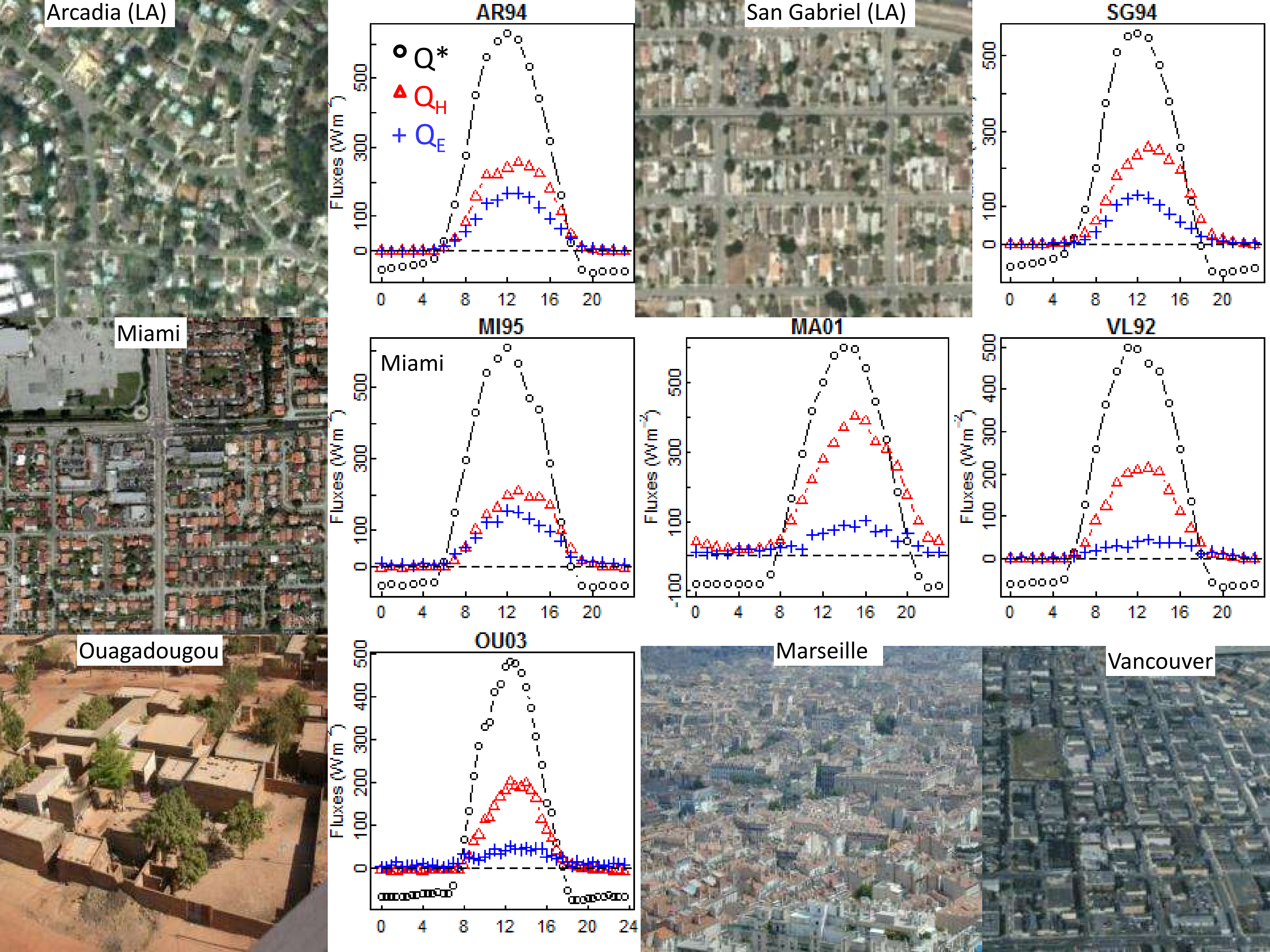
* Annual data



Loridan and Grimmond (2011 JAMC)

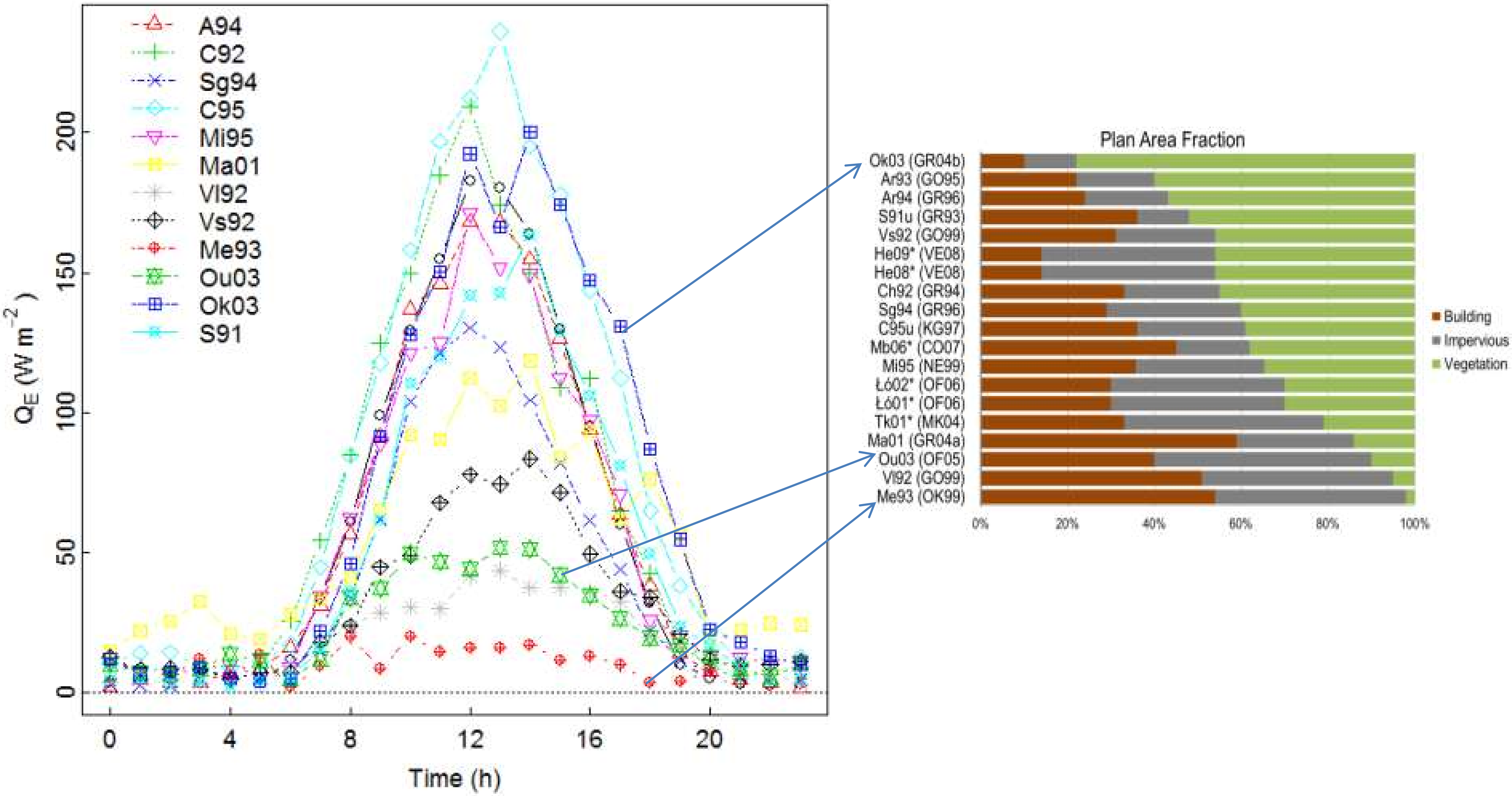


Helsinki: Vesala, Järvi, Nordbo
Tokyo: Moriwaki and Kanda
Melbourne: Coutts and Berringer
Lodz: Offerle, Grimmond and Fortuniak
Ouagadougou: Offerle, Grimmond, Eliasson
Marseille, Miami, Sacramento, Tucson, Vancouver: Grimmond and Oke
Chicago, Los Angeles, Oklahoma City: Grimmond



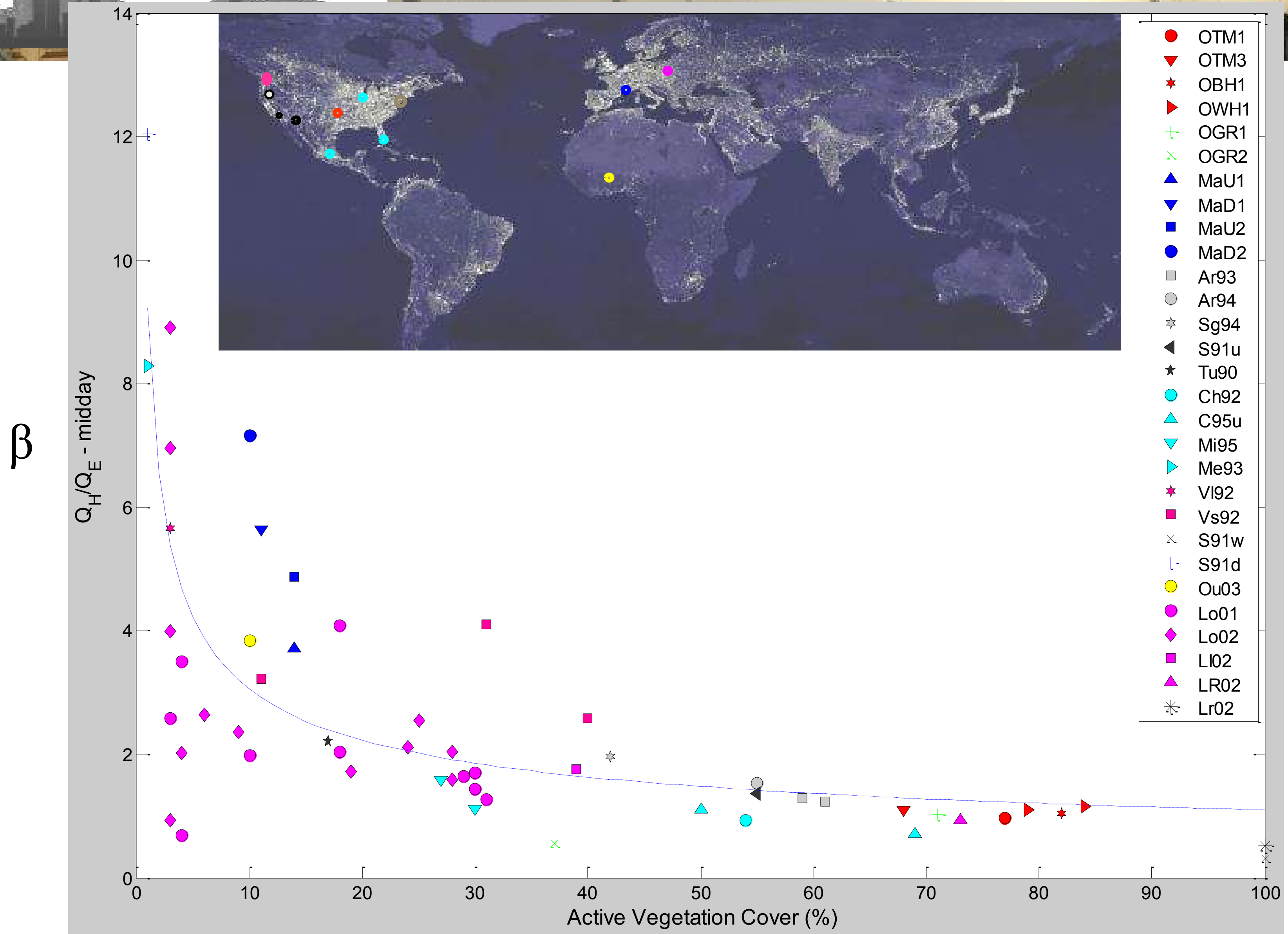
Arcadia (LA)
AR94
Q*
Q_H
Q_E
Fluxes (W m⁻²)
San Gabriel (LA)
SG94
Miami
MI95
Miami
MA01
VL92
Ouagadougou
OU03
Marseille
Vancouver

Variability of Latent Heat Flux: Short observation periods



Cleugh and Grimmond (2012)

Convective Flux Partitioning: Midday Monthly Mean

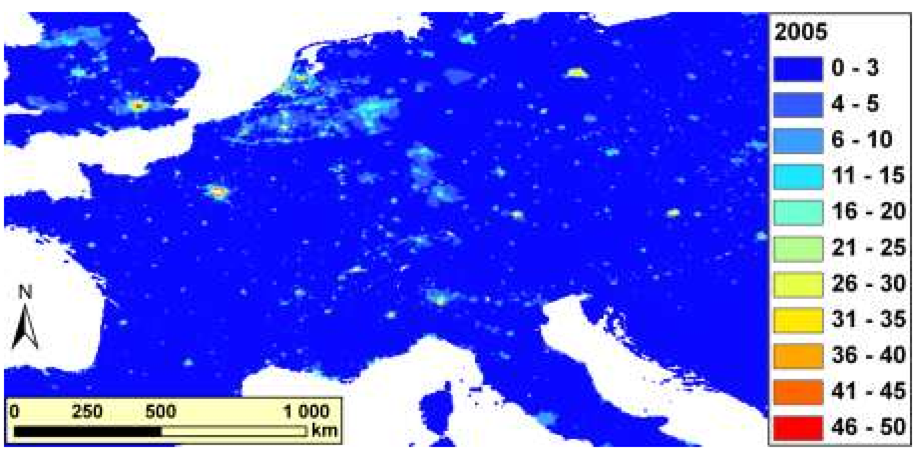


Data from: Grimmond and Oke 2002 *JAM,* Grimmond et al. 2004 *JGR* (Marseille, Ma),
Offerle et al. 2005 IJC, JAM, TAC (Lodz, Lo) Offerle et al. 2005 *JC* (Ouagadougou, Burkina Faso Ou03) OKC (Grimmond)

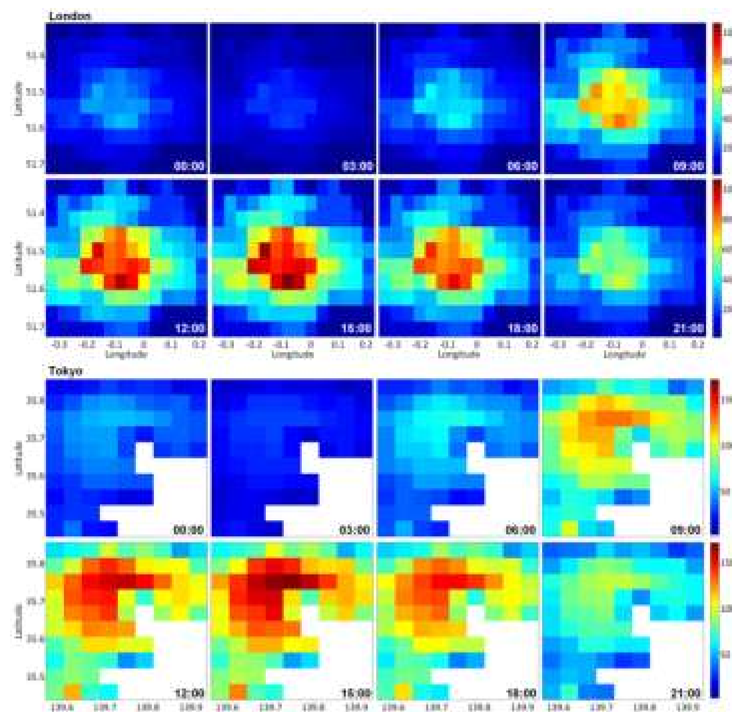
Multi-Site Comparison Considerations

- Incoming **Radiation** ($Q\downarrow = K\downarrow + L\downarrow$) varies
  - $K\uparrow + L\uparrow$ - also dependent on surface characteristics
- **Anthropogenic Heat Flux**
  - Estimated using Allen et al. (2011 IJC): LUCY model
    - Temporal resolution: 60 min
    - Spatial resolution: 2.5 x 2.5 arc minutes (~4.5 km)
    - Spatial extent: 85°N to 58°S

$$Q^* = Q\downarrow - Q\uparrow = K\downarrow - K\uparrow + L\downarrow - L\uparrow$$

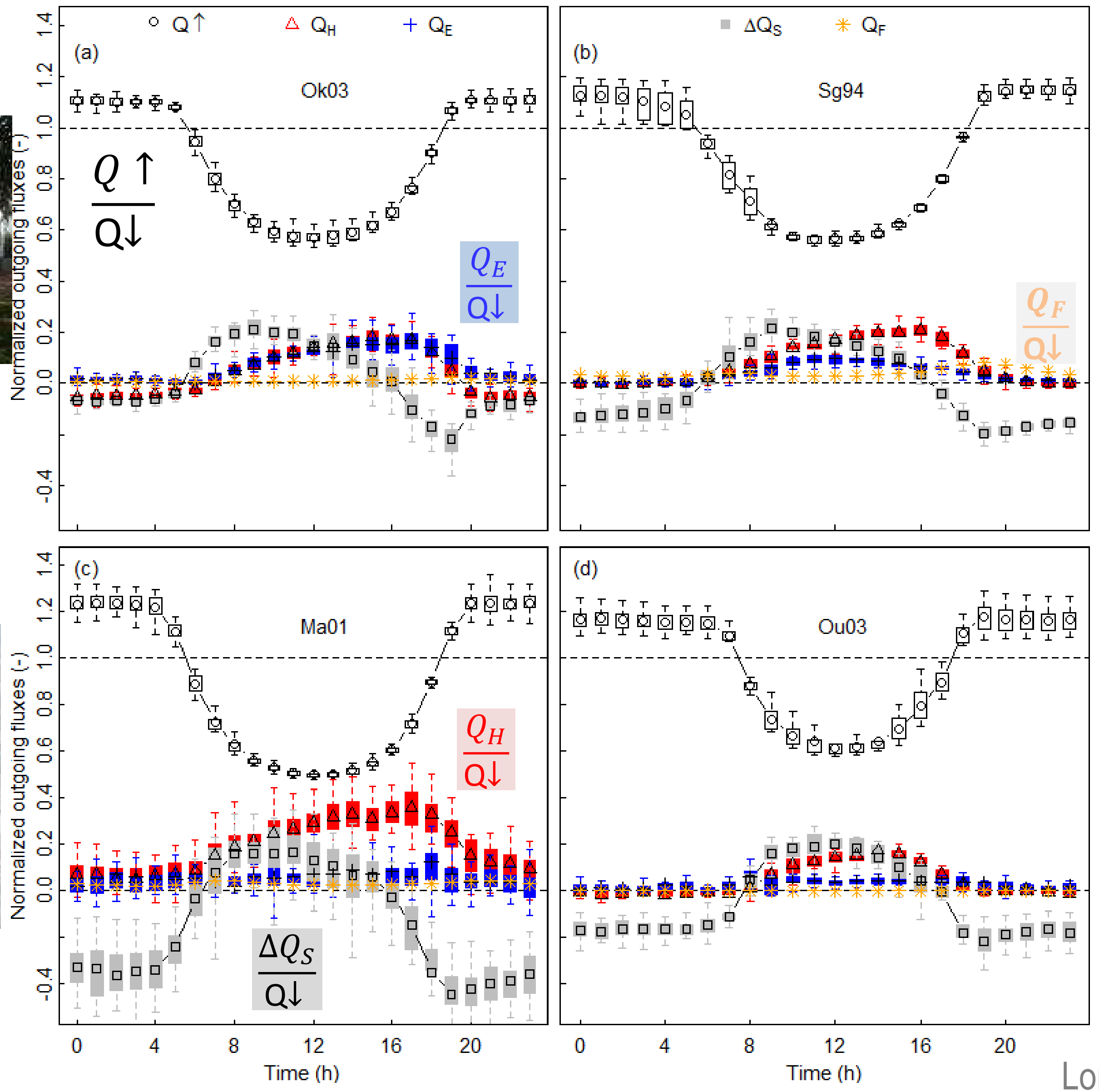


Mean Flux for 2005 Allen et al. (2010)



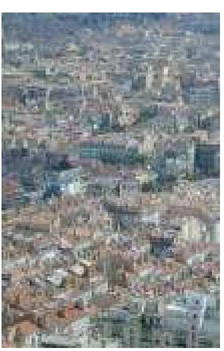
Energy Balance: Incoming Radiation ($Q{\downarrow} = K{\downarrow} + L{\downarrow}$) Normalization

Oklahoma City

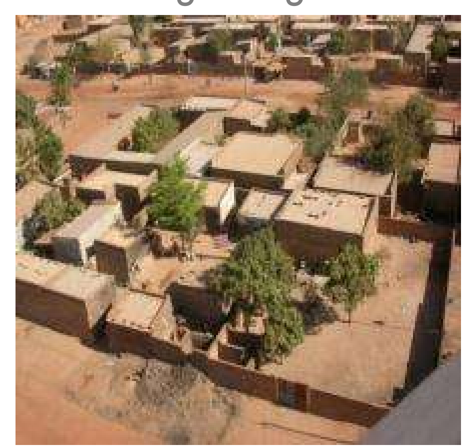


San Gabriel

Marseille



Ouagadougou



Loridan & Grimmond (2012 JAMC)

Midday Period: Fluxes, Bowen Ratio and Vegetated Fraction

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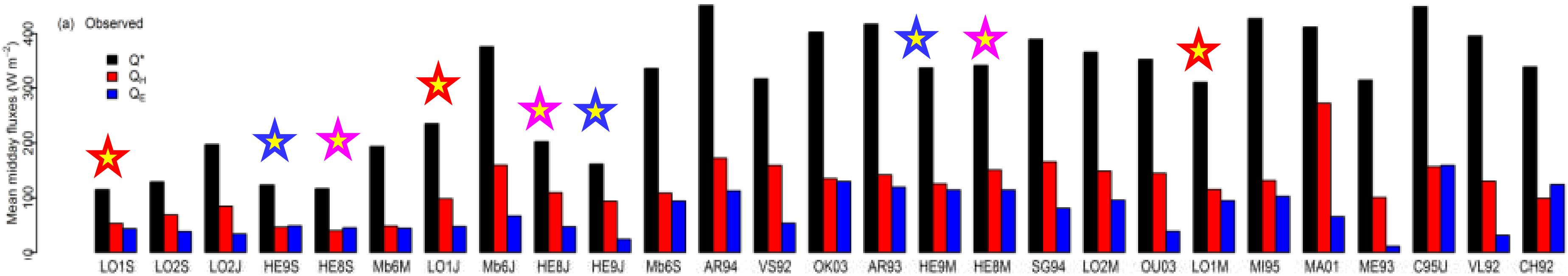
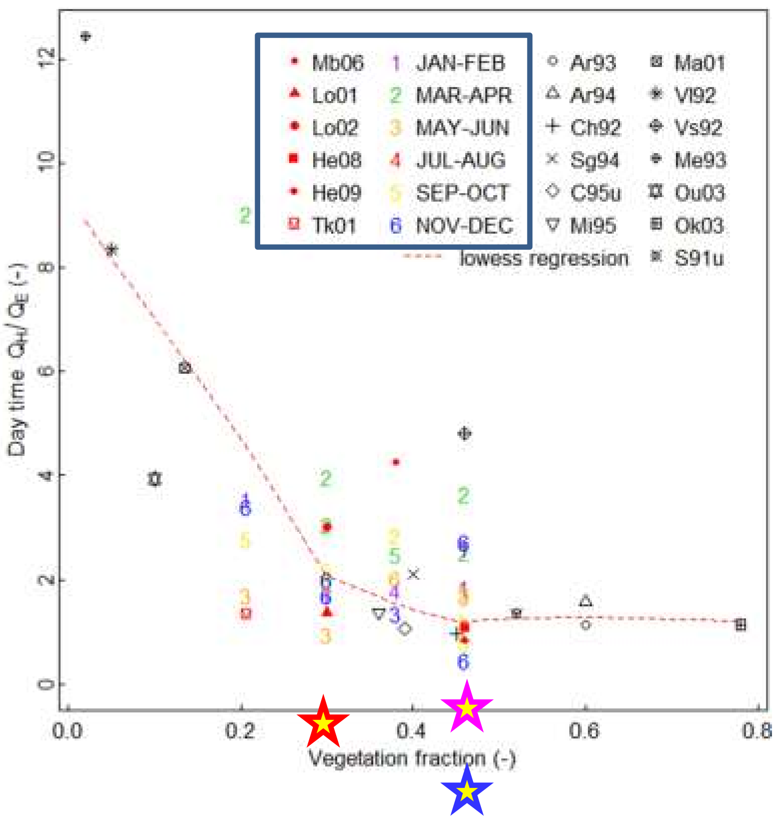


Loridan and Grimmond (2011 QJRMS)

β

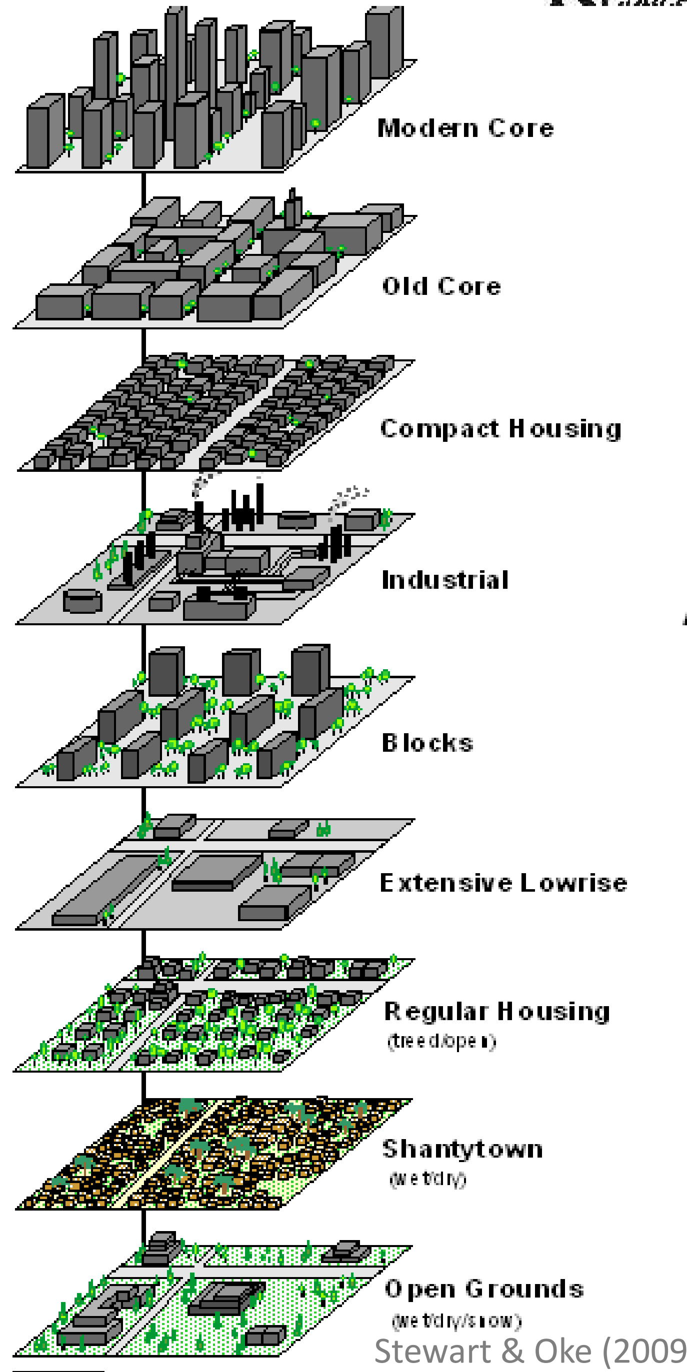


Need dynamic surface characteristics rather than fixed surface characteristics

Loridan and Grimmond (2012 JAMC)

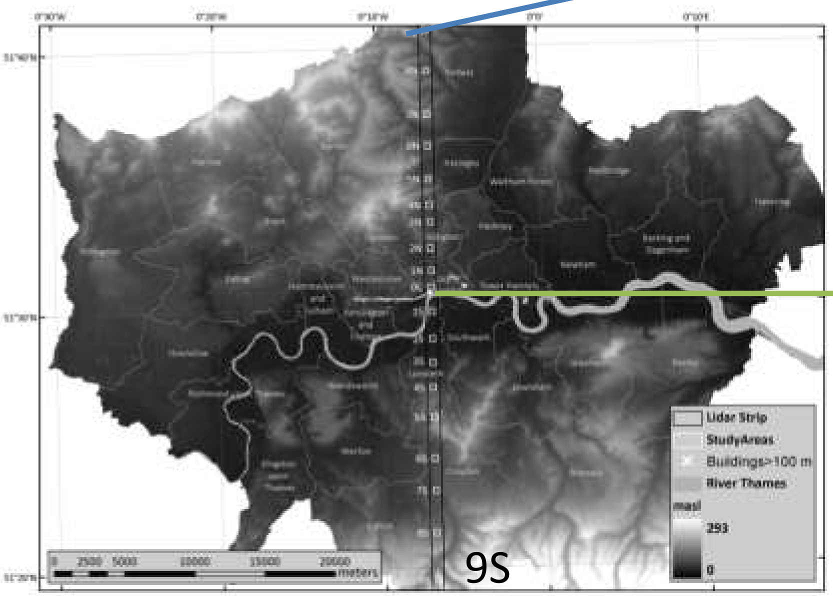
Variability in Urban Surface

Grimmond & Oke 1999 *JAM* 38, 1262-92

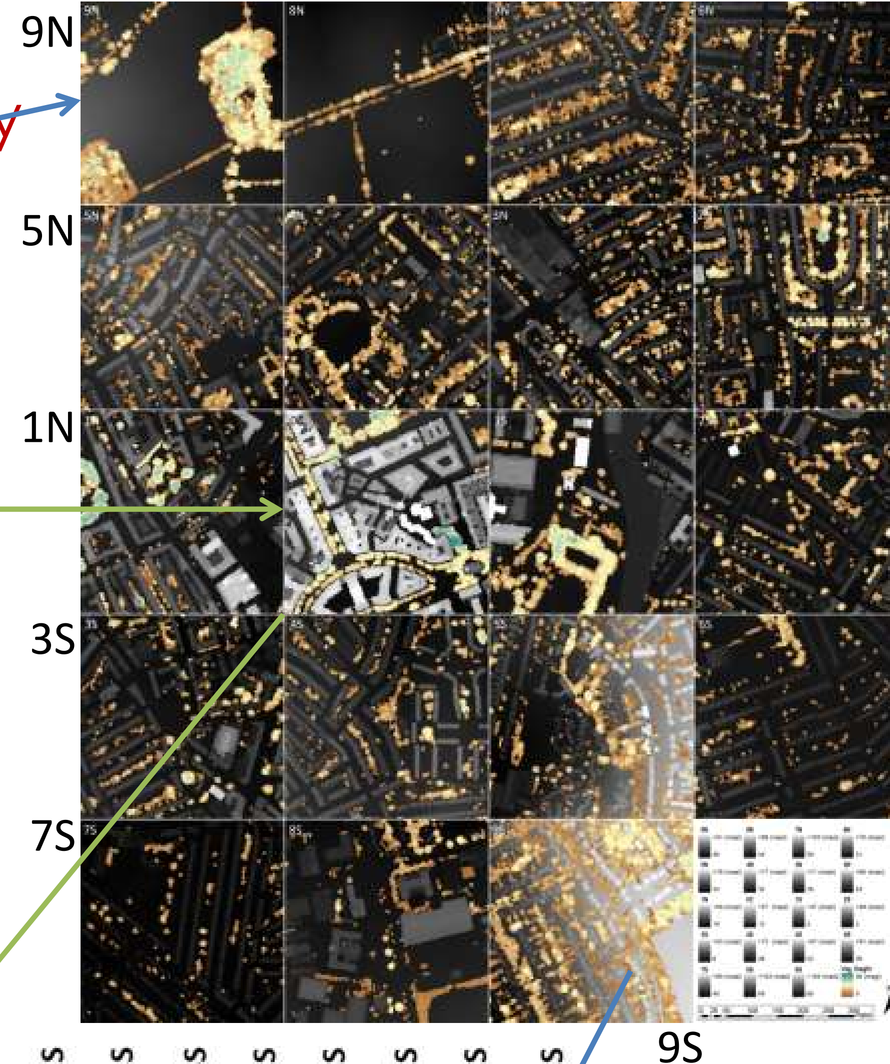


Stewart & Oke (2009)

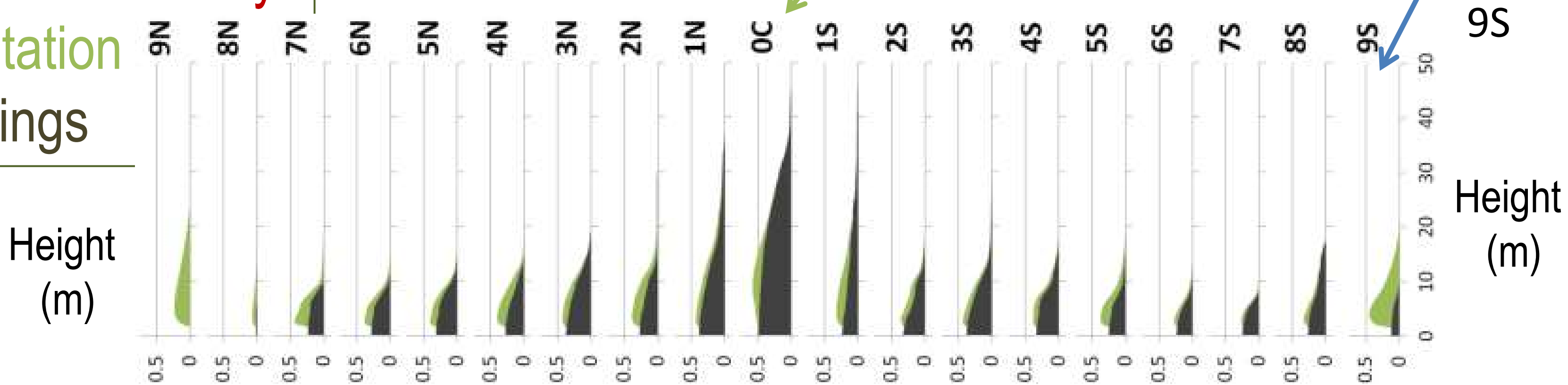
Vegetation Varies Across the City



Lindberg & Grimmond 2011 *Urban Ecosystems*



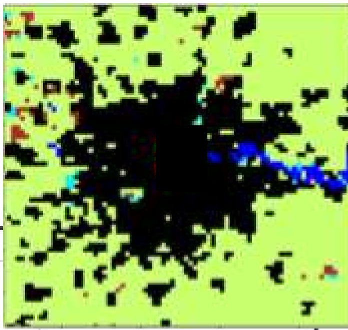
Plan area density
vegetation
buildings

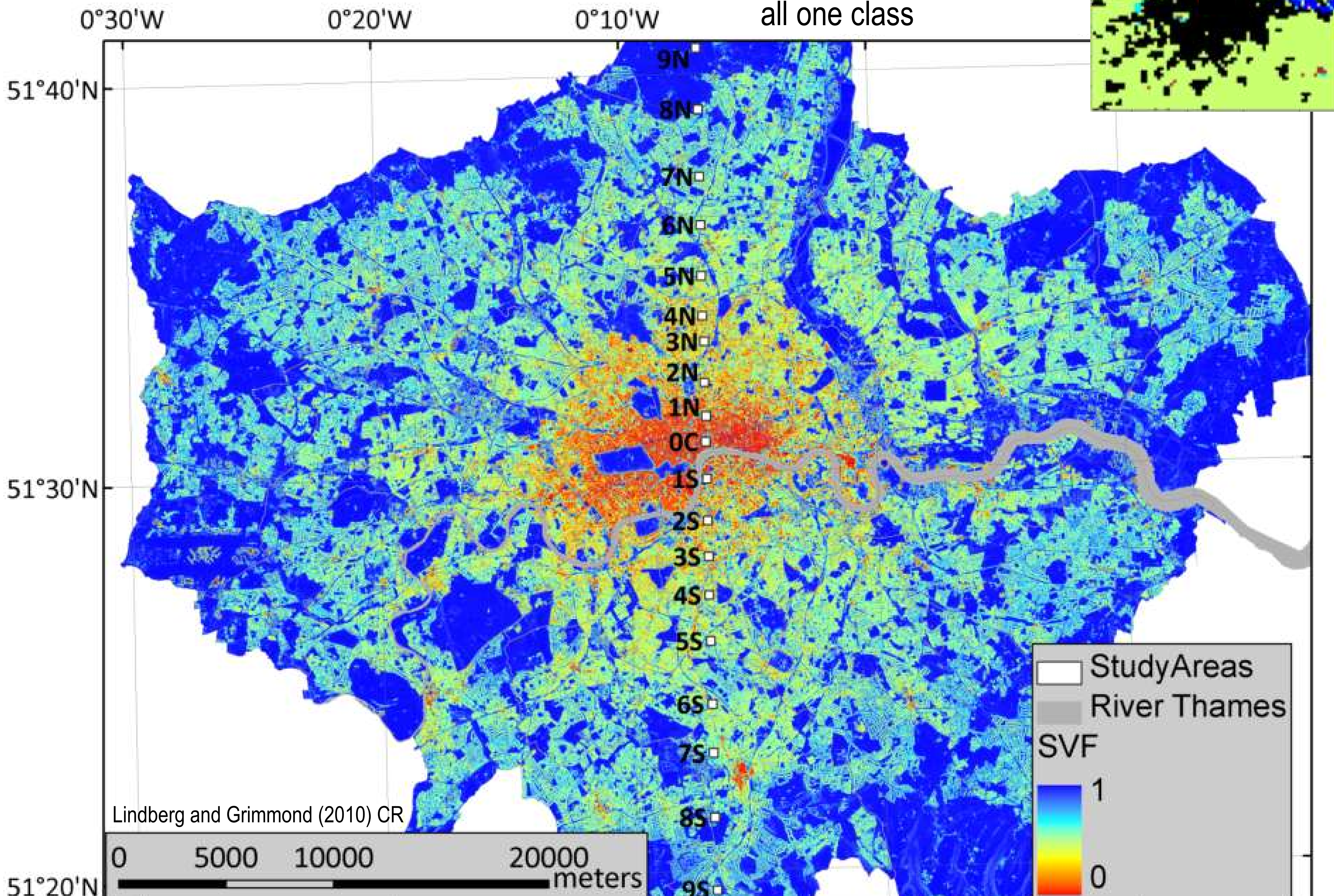


Where do we define class boundaries?

Sky View Factors, London

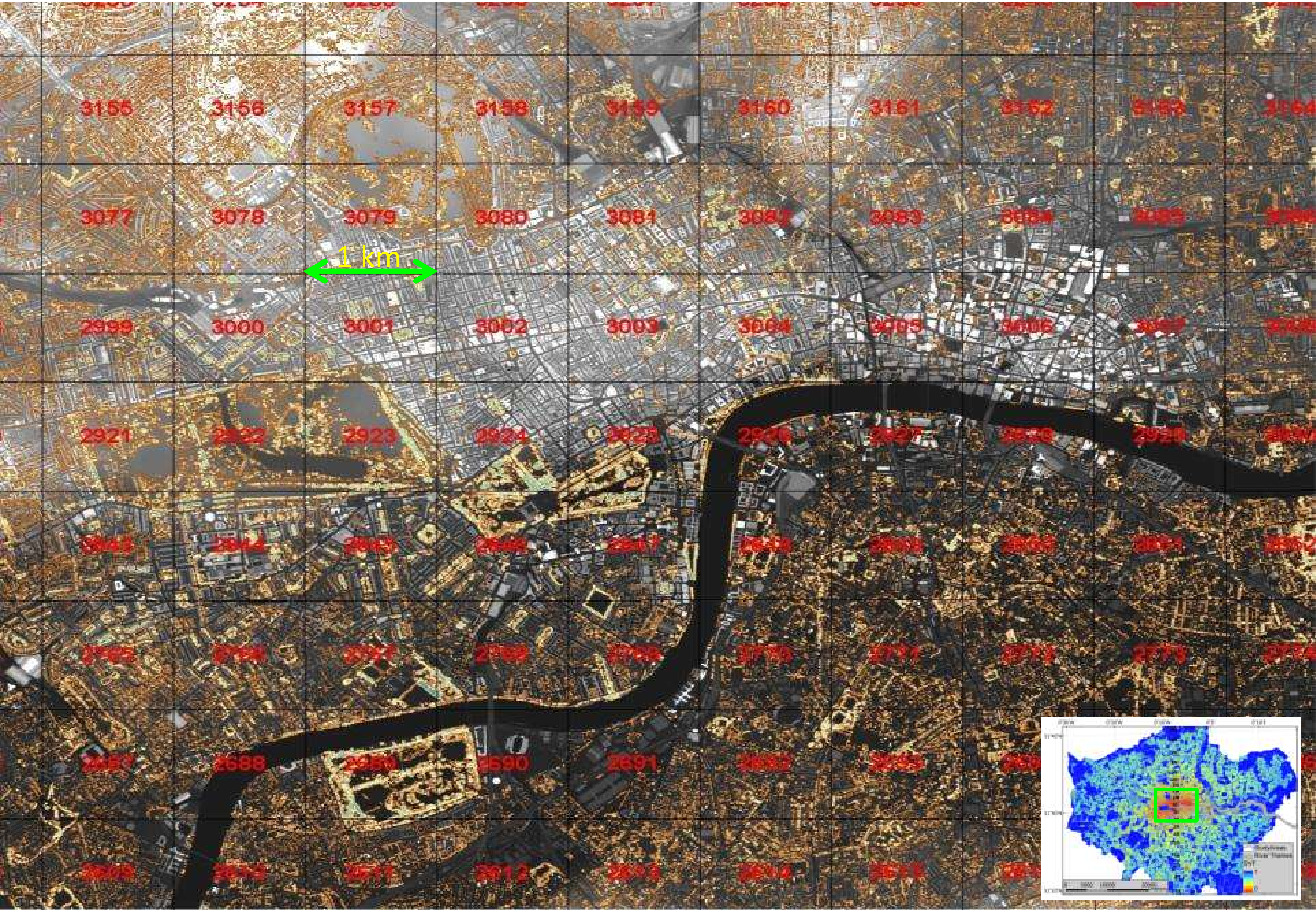
e.g. a USGS classification: all one class





Lindberg and Grimmond (2010) CR

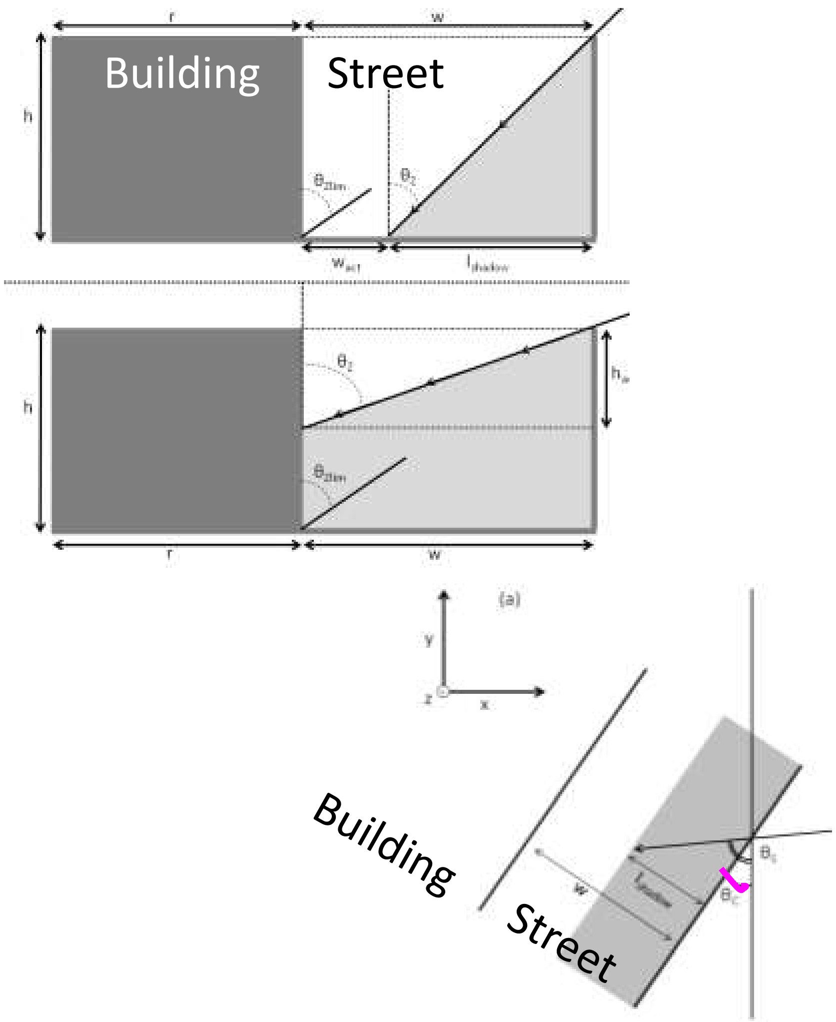
Need objective method to characterize the surface for observations and modelling



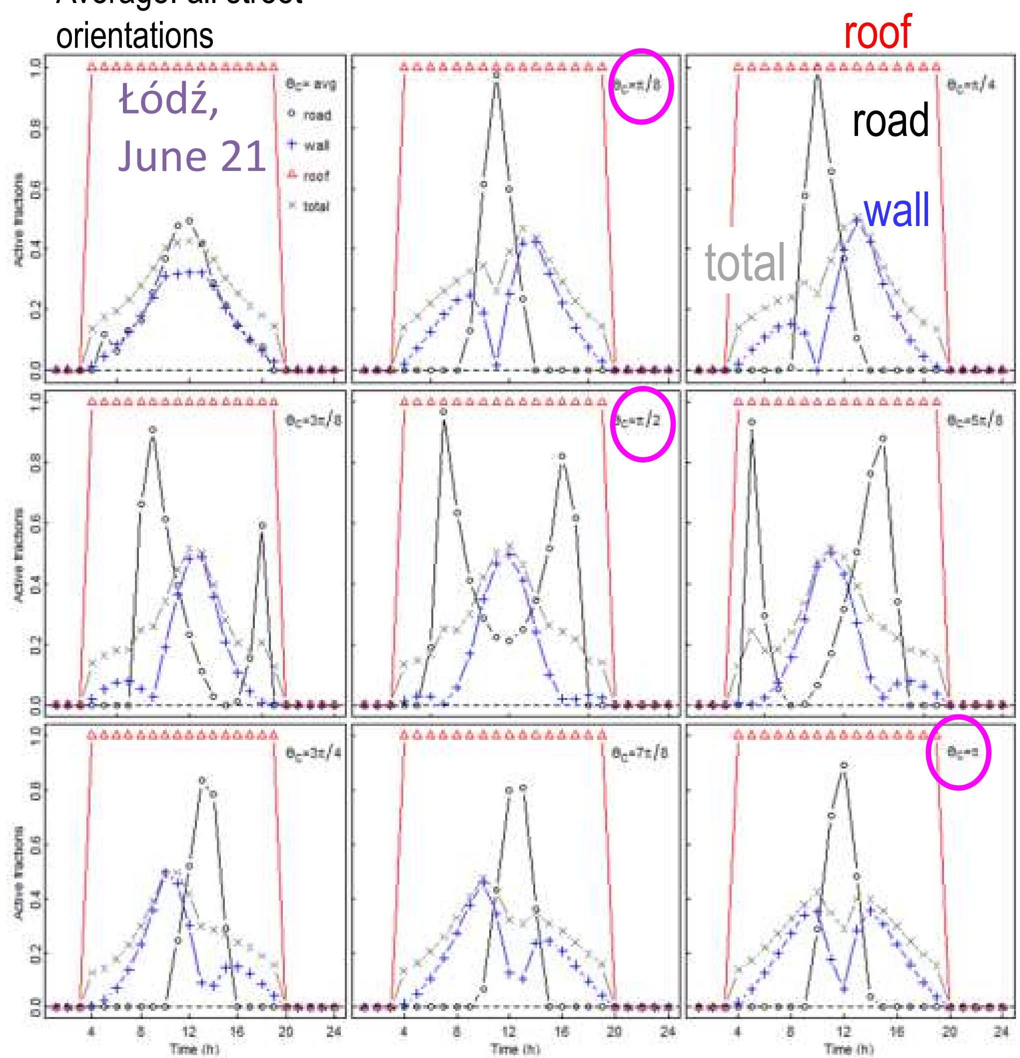
Active Surface Index: **Built** Component

- Dynamic with changing solar forcing through **day** and year

Loridan & Grimmond (2012, JAMC)

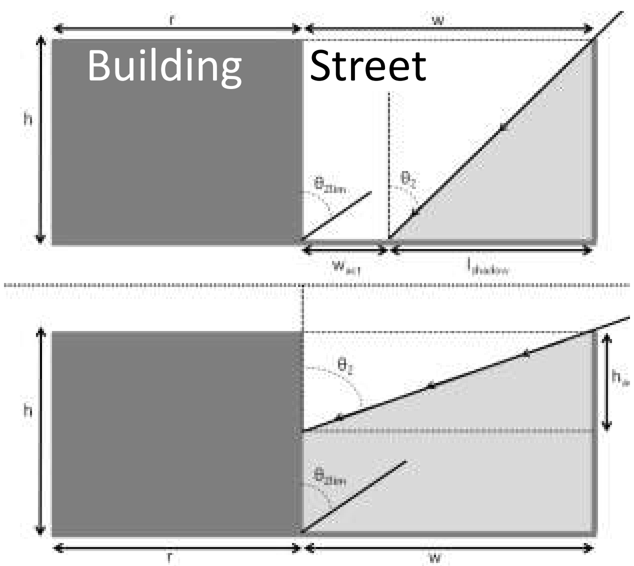


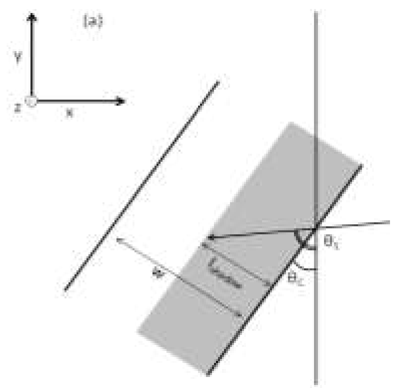
Average: all street orientations

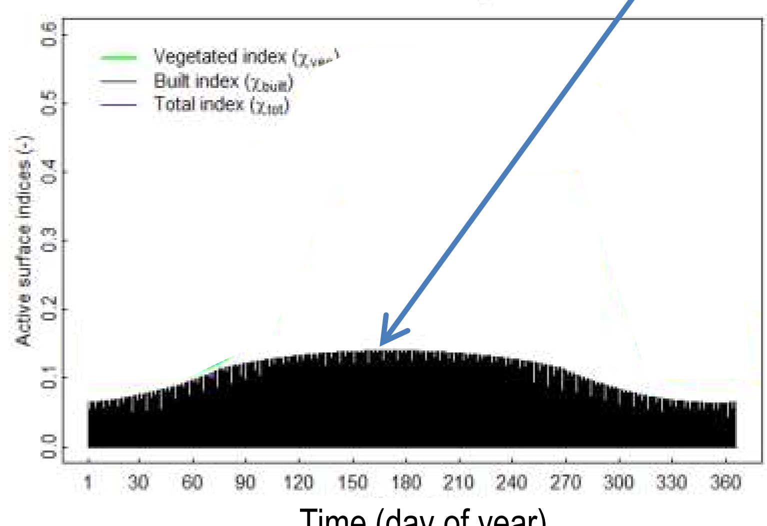


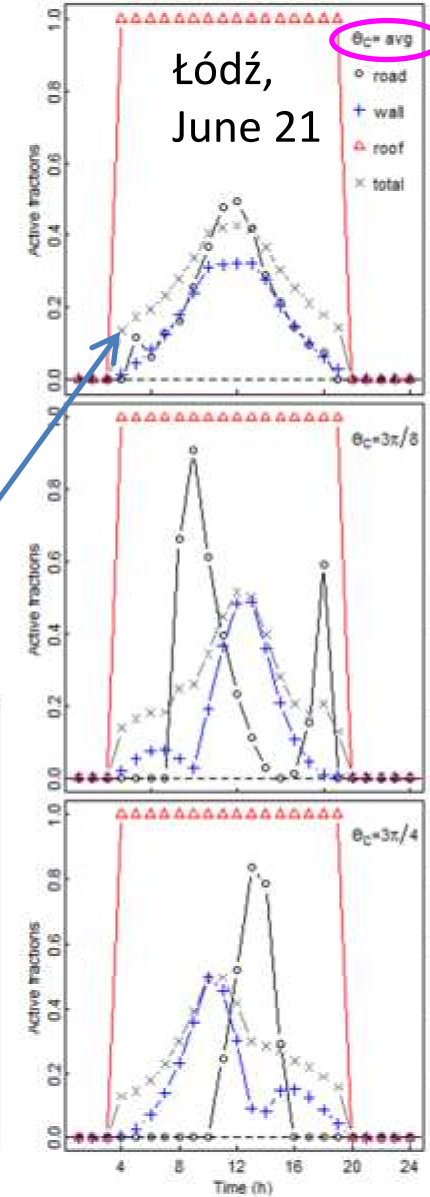
Active Surface Index: **Built** Component

- Dynamic with changing solar forcing through **day** and **year**





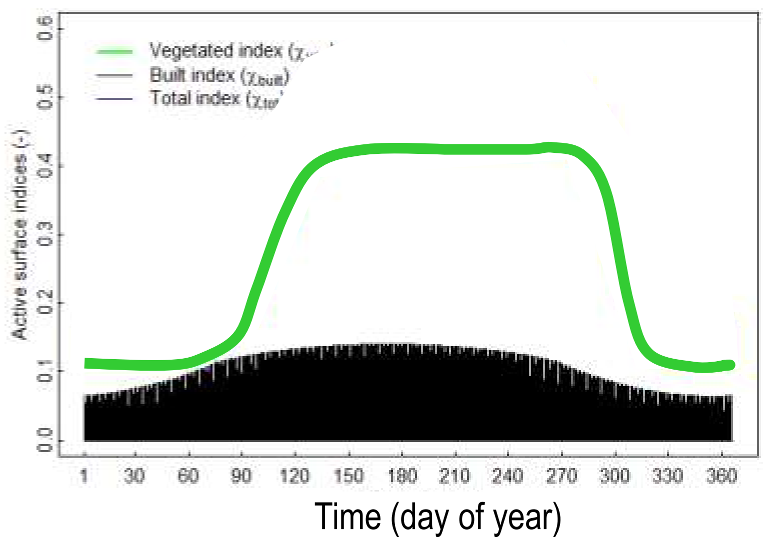




Loridan & Grimmond (2012, JAMC)

Active Surface Index

- **Total** Active Index
  - **Built** component
    - Dynamic with changing solar forcing through day and year
  - **Vegetated** component
    - Changing vegetation cover (phenology)

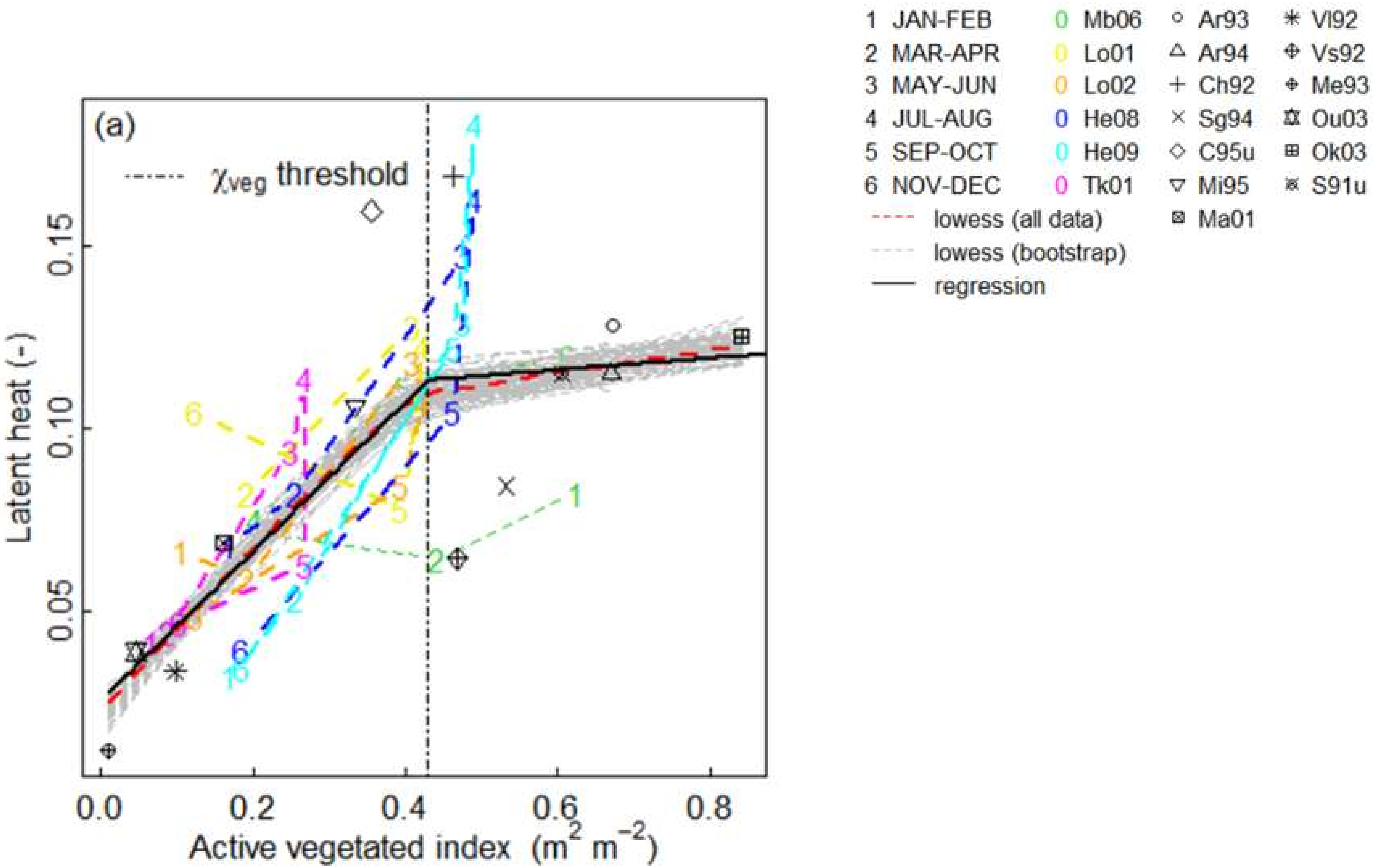


Loridan & Grimmond (2012, JAMC)

Latent Heat Flux & Active Vegetation Index

$$\frac{Q_E}{Q\downarrow}$$

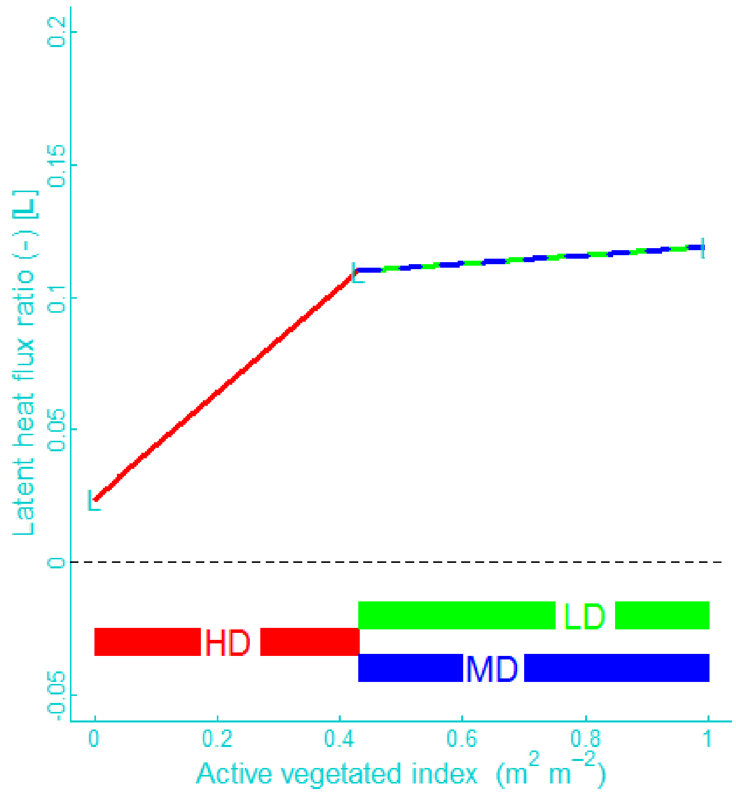
$Q\downarrow = K\downarrow + L\downarrow$



Loridan & Grimmond (2012 JAMC)

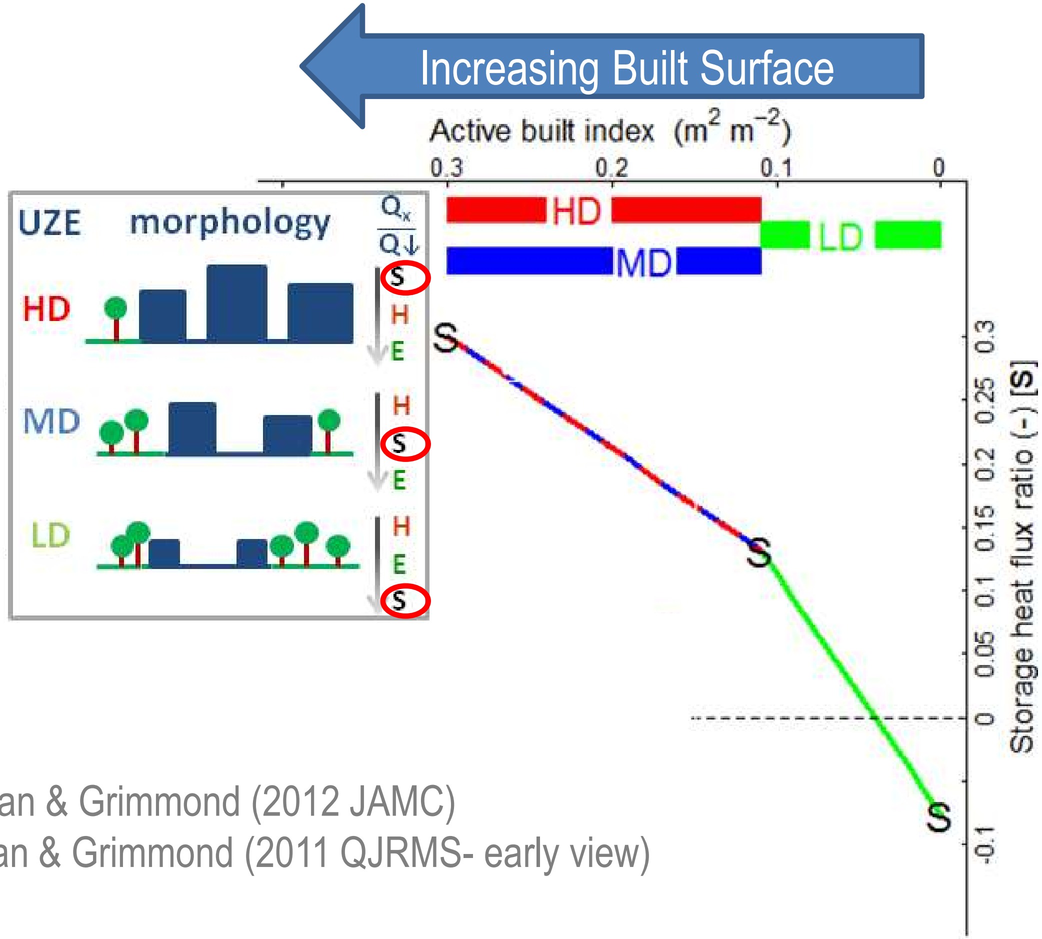
Latent Heat Flux & Active Vegetation Index

Small amounts of vegetation –
Large impact on flux partitioning



Loridan & Grimmond
(2011 QJRMS- early view)

Storage Heat Flux



ΔQS

Q↓

Increasing storage heat

Detailed analysis Loridan & Grimmond (2012 JAMC)

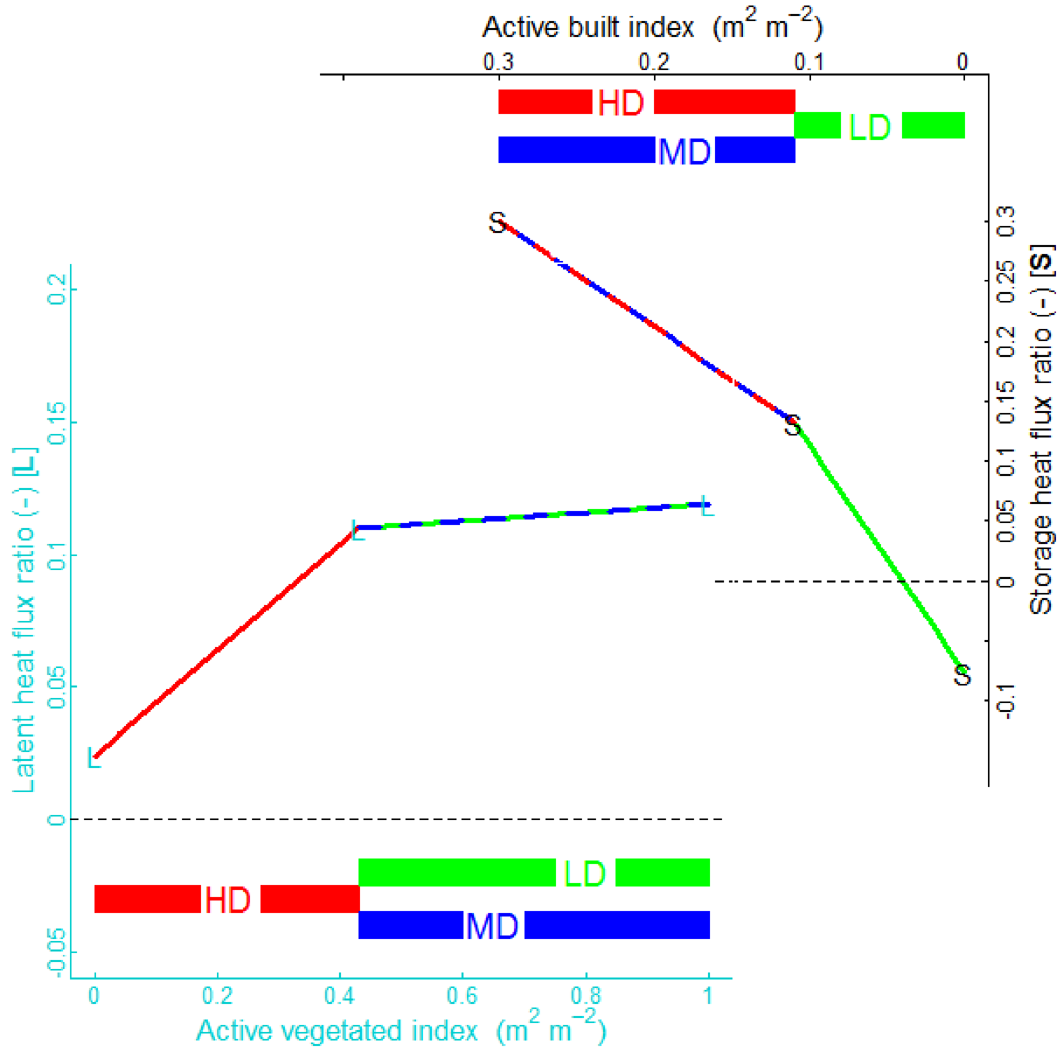
Simplified figure: Loridan & Grimmond (2011 QJRMS- early view)

Midday hours

Building characteristics – Large impact on flux partitioning

Surface Energy Flux Partitioning & Surface Characteristics

Combined – major controls on urban energy flux partitioning

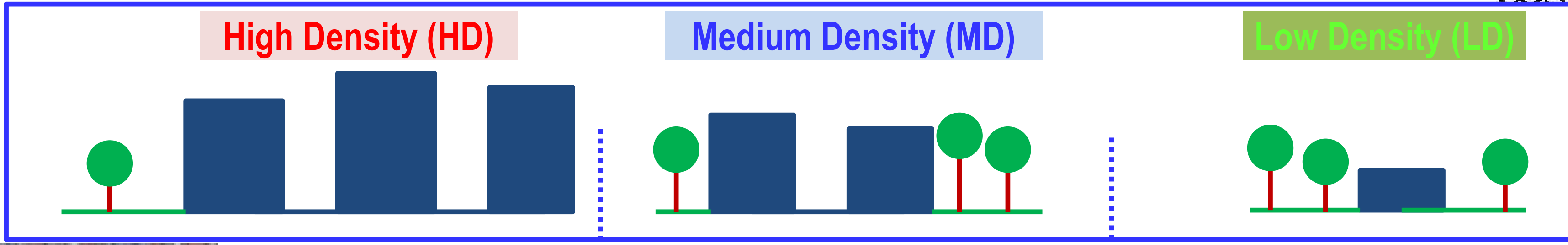


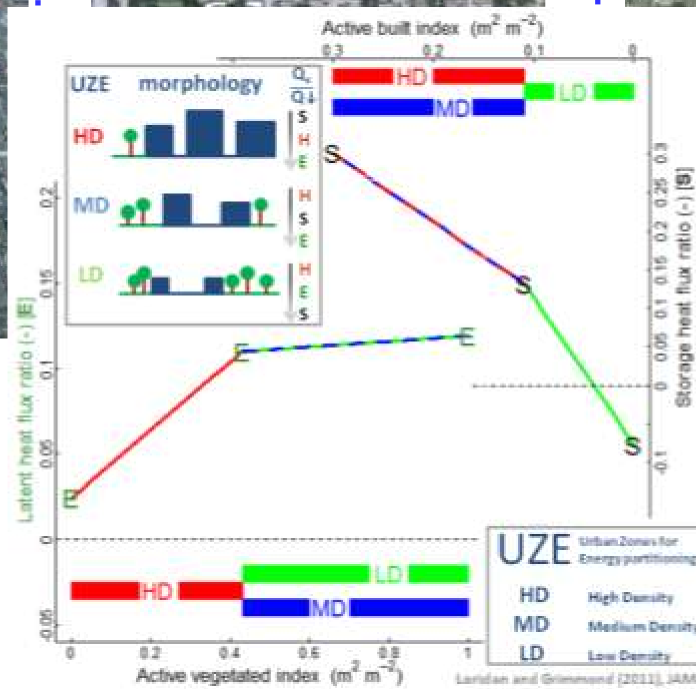
Detail analysis Loridan & Grimmond (2012 JAMC)

Simplified figure: Loridan & Grimmond (2011 QJRMS- early view)

Urban Zones to characterize Energy partitioning (UZE)

KING'S College LONDON





UZE

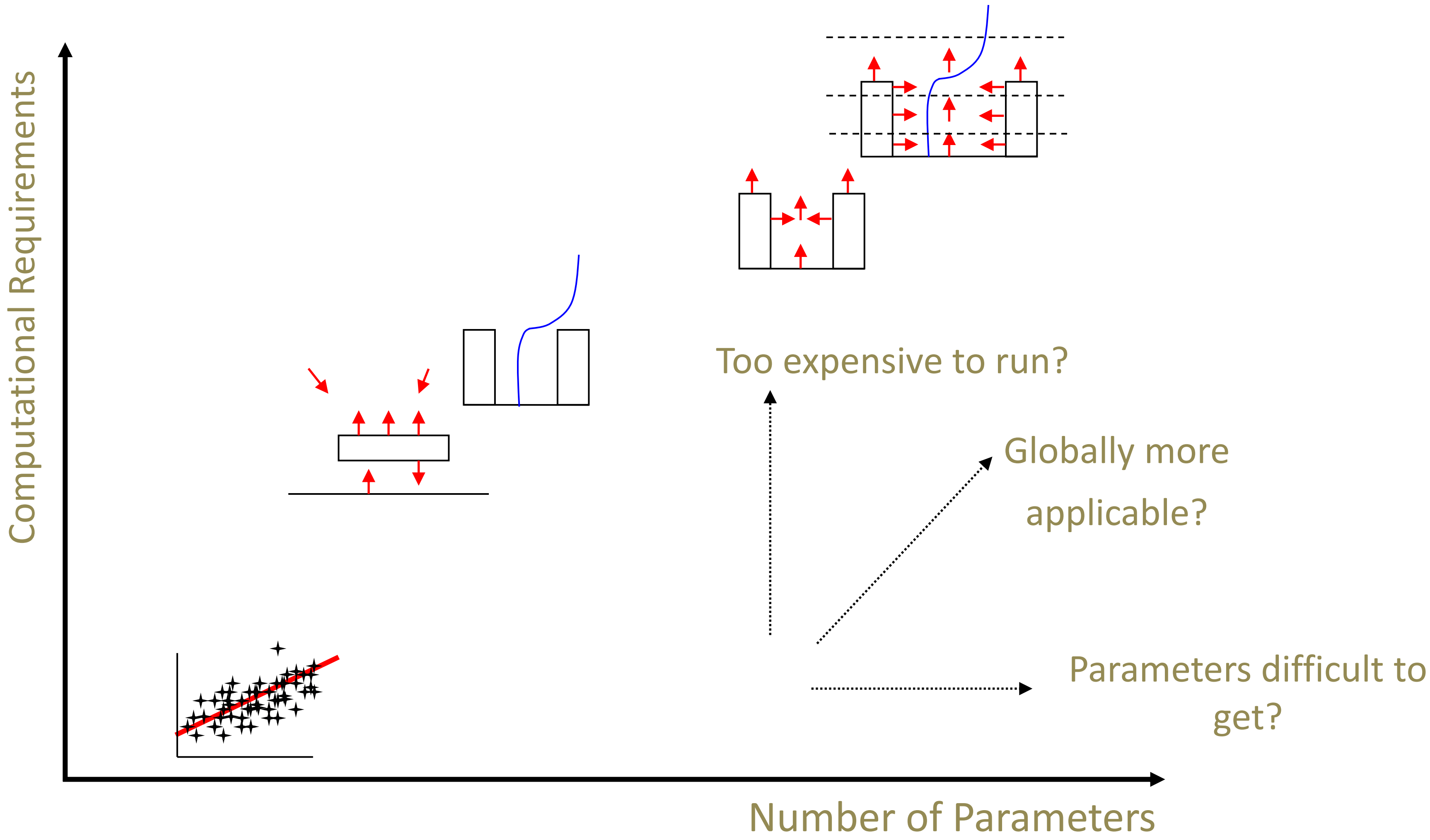
most vegetated: *Low Density*

more urban: *Medium Density*

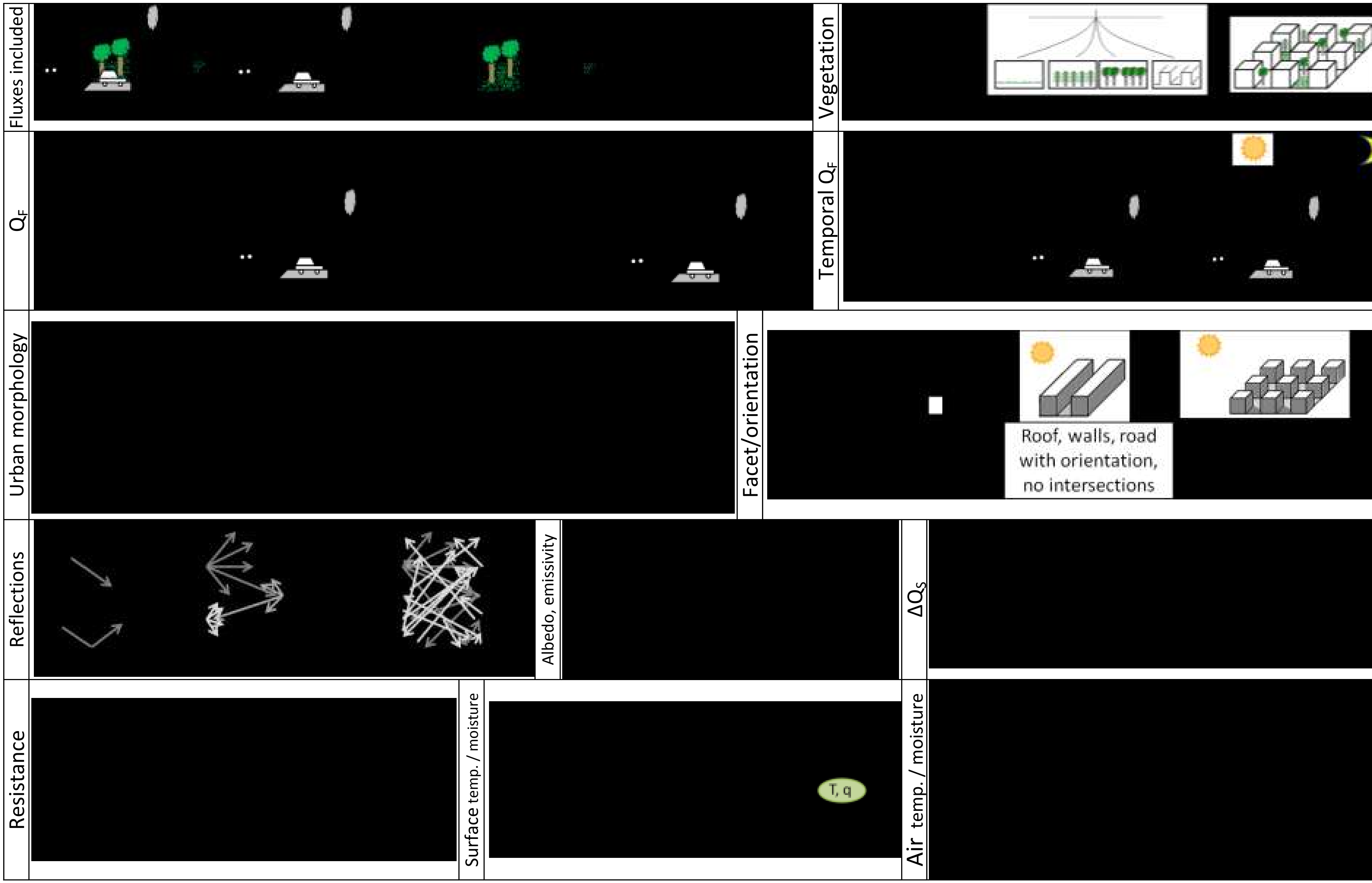
most urban: *High Density*

Loridan & Grimmond (2012a,b JAMC, QJRMS)

Complexity of Urban Land Surface Models

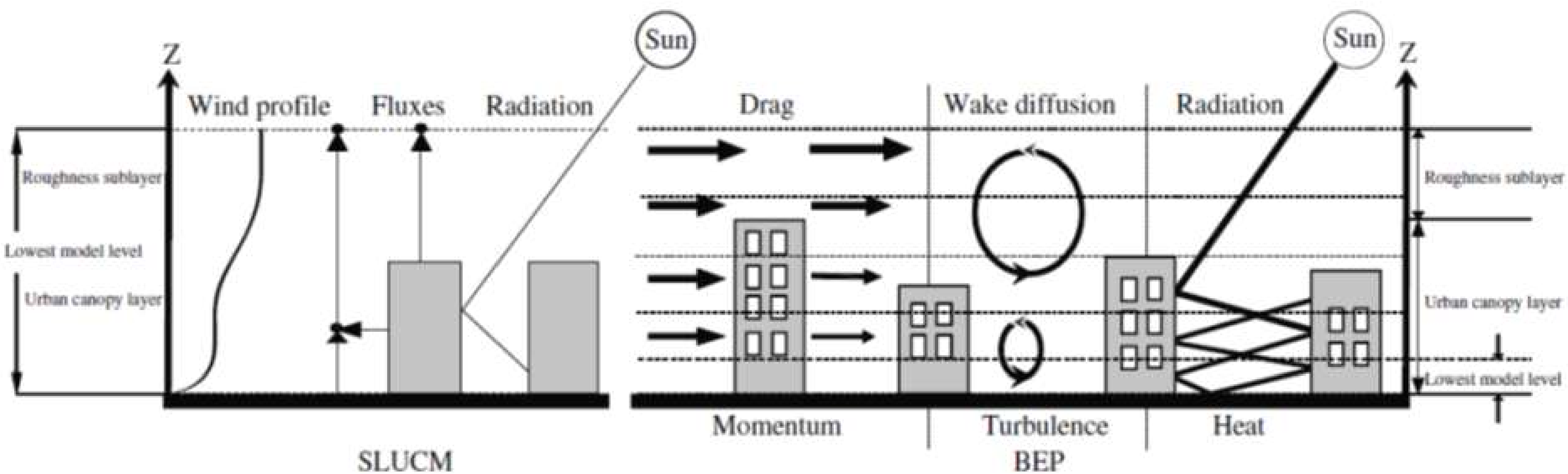


Approaches to Modelling (Grimmond et al. 2011 IJC)



WRF and the Single Layer Urban Canopy Model

- 3 urban schemes are available **in WRF** *:
  1) **Slab scheme** (Noah-Slab): vegetation scheme tuned for urban applications
  2) **Single layer Urban Canopy Model** (SLUCM, Kusaka et al., 2002)
  3) **Multi layer UCM** (Martilli et al., 2002)

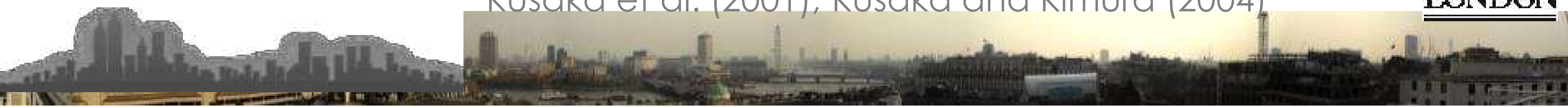


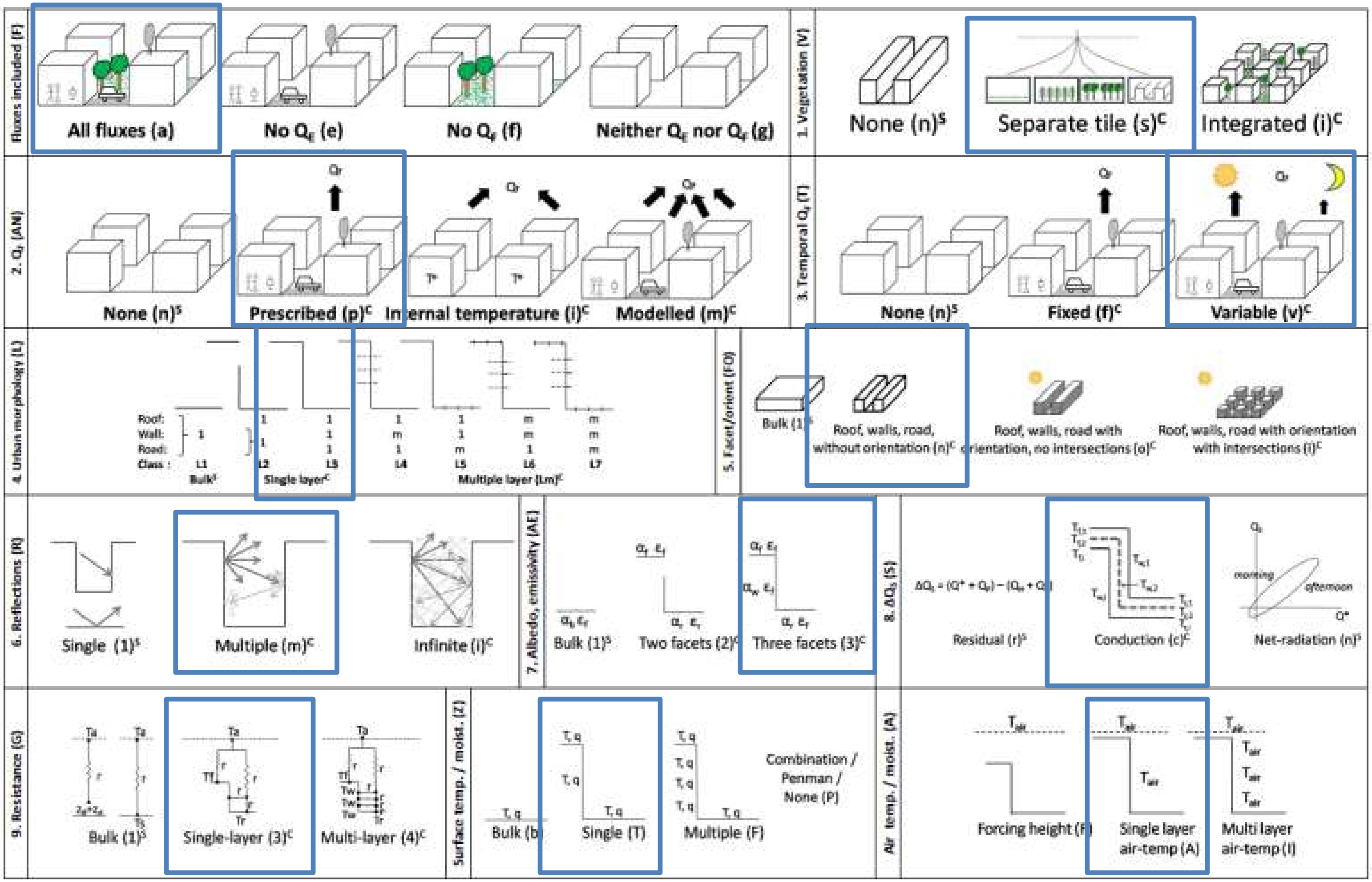
Chen et al. (2011) IJC

* Increasing number of LSM are being included

Single Layer Urban Canopy Model (SLUCM)

Kusaka et al. (2001); Kusaka and Kimura (2004)



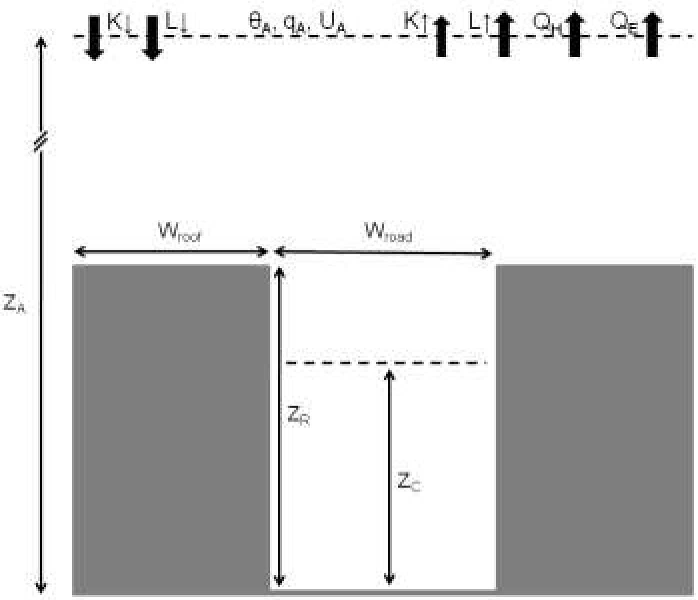


Medium complexity

Input Parameters

NOAH/SLUCM:

Total: 68 parameters

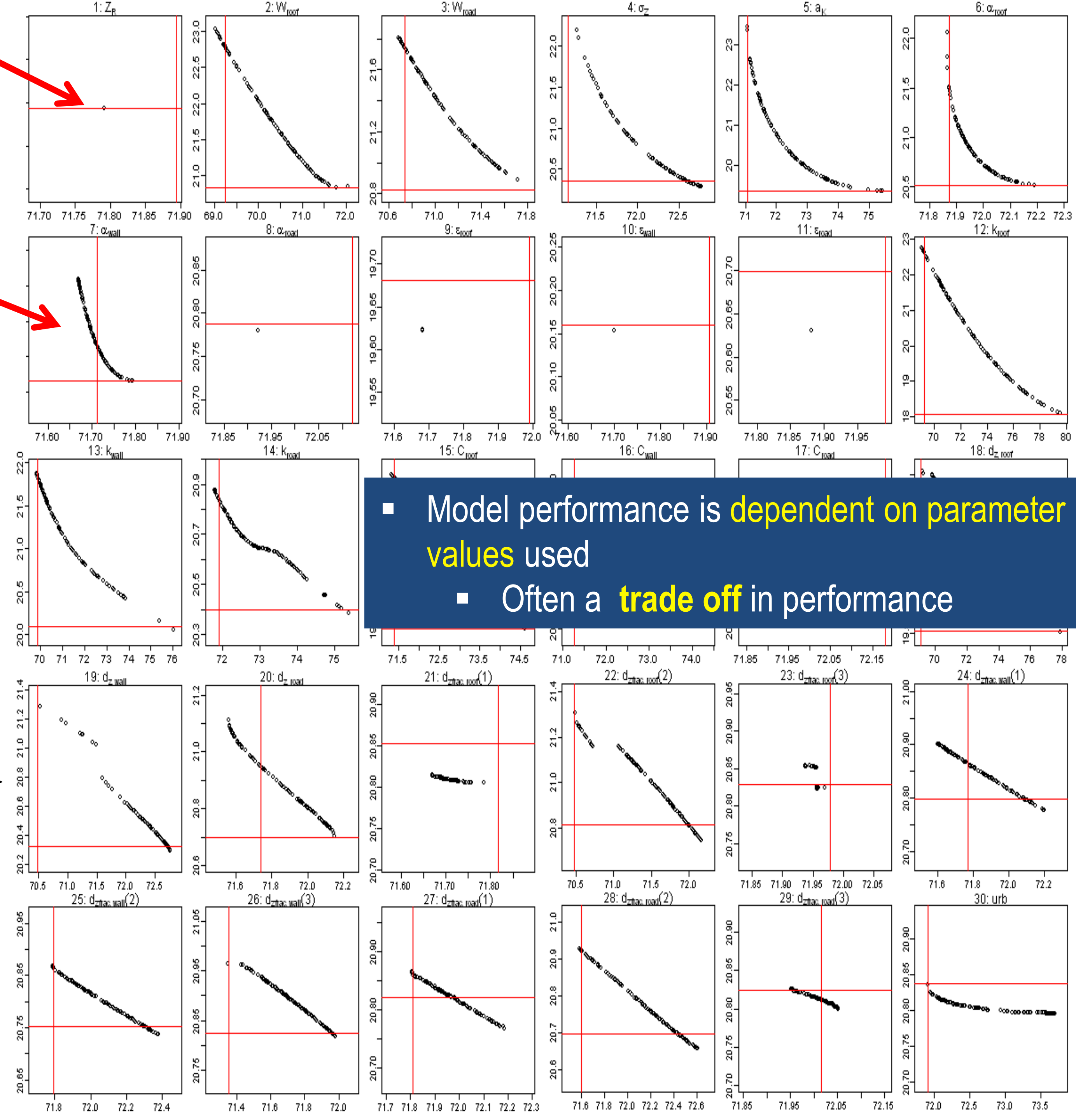


Loridan et al. (2010) QJRMS

	Parameter	Min	Max	Default	Parameter Definition
1	Z_R	12.6	18.6	15.6	Roof height (m)
2	W_{roof}	11.2	31.2	21.2	Roof width (m)
3	W_{road}	3.6	15.6	9.6	Road width (m)
4	σ_Z	1.0	15.0	9.0	Standard deviation of roof height (m)
5	a_K	0.5	2.0	1.29	Empirical coefficient from Kanda et al. (2007)
6	α_{roof}	0.05	0.4	0.22	Roof albedo (-)
7	α_{wall}	0.05	0.55	0.20	Wall albedo (-)
8	α_{road}	0.05	0.25	0.08	Road albedo (-)
9	ε_{roof}	0.85	0.98	0.90	Roof emissivity (-)
10	ε_{wall}	0.85	0.98	0.90	Wall emissivity (-)
11	ε_{road}	0.85	0.98	0.94	Road emissivity (-)
12	k_{roof}	0.19	1.5	0.90	Conductivity of roof materials ($W\ m^{-1}\ K^{-1}$)
13	k_{wall}	0.09	2.3	0.55	Conductivity of wall materials ($W\ m^{-1}\ K^{-1}$)
14	k_{road}	0.03	2.1	1.77	Conductivity of road materials ($W\ m^{-1}\ K^{-1}$)
15	C_{roof}	$0.6*10^6$	$2.3*10^6$	$1.77*10^6$	Heat capacity of roof materials ($J\ m^{-3}\ K^{-1}$)
16	C_{wall}	$0.4*10^6$	$2.3*10^6$	$1.67*10^6$	Heat capacity of wall materials ($J\ m^{-3}\ K^{-1}$)
17	C_{road}	$0.3*10^6$	$2.3*10^6$	$1.89*10^6$	Heat capacity of road materials ($J\ m^{-3}\ K^{-1}$)
18	$d_{z,roof}$	0.05	0.5	0.32	Total thickness of roof layers (m)
19	$d_{z,wall}$	0.1	1.0	0.26	Total thickness of wall layers (m)
20	$d_{z,road}$	0.5	2.0	1.24	Total thickness of road layers (m)
21	$d_{zfrac,roof}$ (1)	0.02	0.1	0.062	Fraction of $d_{z,roof}$ covered by layer 1
22	$d_{zfrac,roof}$ (2)	0.1	0.49	0.468	Fraction of $d_{z,roof}$ covered by layer 2
23	$d_{zfrac,roof}$ (3)	0.1	0.4	0.375	Fraction of $d_{z,roof}$ covered by layer 3
24	$d_{zfrac,wall}$ (1)	0.02	0.1	0.038	Fraction of $d_{z,wall}$ covered by layer 1
25	$d_{zfrac,wall}$ (2)	0.1	0.3	0.154	Fraction of $d_{z,wall}$ covered by layer 2
26	$d_{zfrac,wall}$ (3)	0.1	0.59	0.577	Fraction of $d_{z,wall}$ covered by layer 3
27	$d_{zfrac,road}$ (1)	0.02	0.1	0.032	Fraction of $d_{z,road}$ covered by layer 1
28	$d_{zfrac,road}$ (2)	0.1	0.4	0.16	Fraction of $d_{z,road}$ covered by layer 2
29	$d_{zfrac,road}$ (3)	0.1	0.49	0.4	Fraction of $d_{z,road}$ covered by layer 3
30	urb	0.764	0.964	0.864	Urban fraction (-)
31	R_{cmin}	40	400	170	Stomatal resistance ($s\ m^{-1}$)
32	R_{gl}	30	100	100	Radiation stress parameter (-)
33	h_S	36.25	54.56	39.18	Vapor pressure deficit parameter (-)
34	α_{veg}	0.10	0.30	0.23	Vegetation albedo (-)
35	ε_{veg}	0.88	0.97	0.93	Vegetation emissivity (-)
36	$z_{0,\ veg}$	0.03	1.6	0.05	Roughness length for momentum - vegetation (m)
37	Θ_s	0.339	0.476	0.465	Maximum soil moisture content ($m^3\ m^{-3}$)
38	Θ_{ref}	0.236	0.453	0.382	Reference soil moisture content ($m^3\ m^{-3}$)
39	Θ_w	0.010	0.2	0.103	Wilting point ($m^3\ m^{-3}$)
40	Θ_{dry}	0.010	0.2	0.103	Dry soil moisture content ($m^3\ m^{-3}$)
41	LAI	1.0	5.0	3.0	Leaf Area Index ($m^3\ m^{-3}$)
42	σ_f	0.1	0.8	0.7	Green vegetation fraction (-)
43	QTZ	0.10	0.92	0.35	Soil quartz content (-)
44	C_{soil}	$0.5*10^6$	$4.0*10^6$	$1.26*10^6$	Soil heat capacity ($J\ m^{-3}\ K^{-1}$)
45	C_{ZIL}	0.01	1.0	0.1	Zilitinkevitch parameter

Optimum state: 100 solutions clustered together

No optimum state: 'trade-offs' in the modelling of the 2 fluxes



- Model performance is dependent on parameter values used
  - Often a **trade off** in performance

RMSE for Q^* ($W\ m^{-2}$)

RMSE for Q_H ($W\ m^{-2}$)

Objective space of 100 samples: each point is an optimized model run

○ Optimized samples

Best *single* objective run (for Q^* and Q_H)

Loridan et al. (2010) QJRMS

SLUCM sensitivity

(a)	Parameter	Default	Optimum	**Gain in Q*** (ΔRMSE)	Impact on Q_H (ΔRMSE)	Impact on Q_E (ΔRMSE)
1	α_{roof}	0.22	0.135	-12.39	6.35	0
2	a_K	1.29	0.529	-7.60	6.17	0
3	α_{wall}	0.2	0.052	-6.62	0.56	0
4	α_{veg}	0.23	0.102	-6.36	1.17	-0.74
5	W_{roof}	21.2	11.2	-3.54	-2.89	0
6	W_{road}	9.6	15.6	-3.21	-1.03	0

Rankings for Q* and Q_H :
value change **which leads to the best improvement** from the default

Important to know which **parameters** the model is **most sensitive** to

For applications: important to know the model can **respond** to the **appropriate changes** in parameter values

(b)	Parameter	Default	Optimum	**Gain in Q_H** (ΔRMSE)	Impact on Q* (ΔRMSE)	Impact on Q_E (ΔRMSE)
1	k_{roof}	0.9	1.495	-3.38	0.78	0
2	$d_{z,roof}$	0.32	0.16	-2.93	0.49	0
3	W_{roof}	21.2	11.2	-2.89	-3.54	0
4	k_{wall}	0.55	2.3	-2.22	-0.96	0
5	a_K	1.29	1.999	-1.90	7.12	0
6	σ_Z	9	3.168	-1.80	7.55	0

Loridan et al. (2010) QJRMS

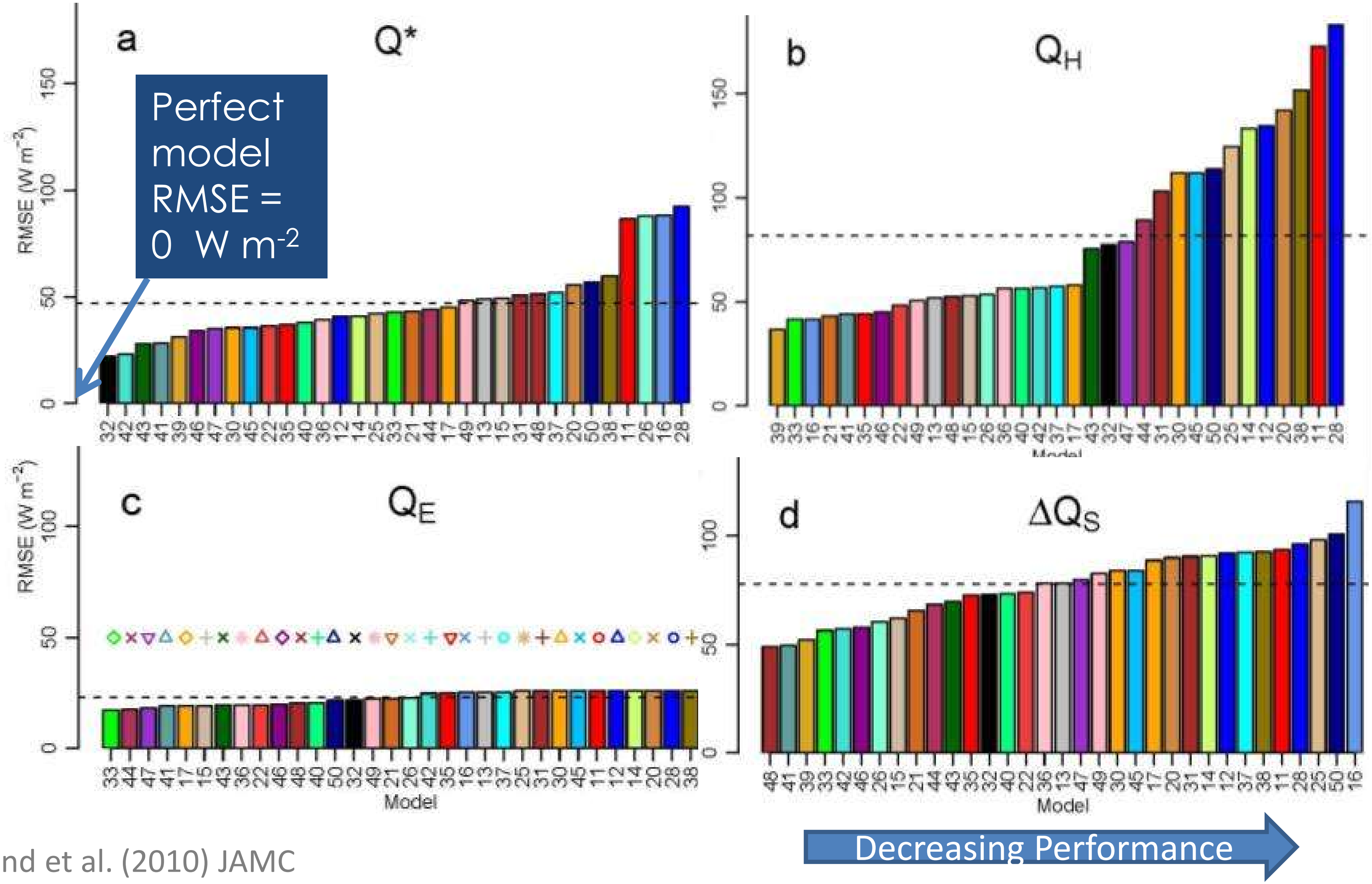
PILPS – Urban: International Urban Energy Balance Model Comparison

Code	Model Name	References	Versions	Groups
BEP02	Building Effect Parameterization	Martilli et al. (2002)	1	1
BEP_BEM08	BEP coupled with Building Energy Model	Martilli et al. (2002), Salamanca et al. (2009),Salamanca and Martilli (2009)	1	1
CLMU	Model - Urban	Oleson et al. (2008a, b)	1	1
GCTTC	Green Cluster Thermal Time Constant model	Shashua-Bar and Hoffman (2002; 2004)	1	1
IISUCM	Science Urban Canopy Model	Kawamoto and Ooka (2006; 2009a; b)	1	1
JULES	Joint Land Environment Simulator	Essery et al. (2003), Best (2005), Best et al. (2006)	4	2
LUMPS	Local-scale Urban Meteorological Parameterization Scheme	Grimmond and Oke (2002), Offerle et al. (2003)	2	1
NKUA	Model	Dandou et al. (2005)	1	1
MORUSES	Met Office Reading Urban Surface Exchange Scheme	Harman et al. (2004 a,b), Porson et al. (2009)	2	1
MUCM	Multi-layer Urban Canopy Model	Kondo and Liu (1998), Kondo et al. (2005)	1	1
NJU--S	Nanjing University Urban Canopy Model-single layer	Masson(2000), Kusaka (2001)	1	1
NJUC-UM-M	Nanjing University Urban Canopy Model-multiple layer	Kondo et al.(2005), Kanda(2005a; b)	1	1
NSLUCM / NSLUCMK / NSLUCM-WRF	Noah land surface model/Single-layer Urban Canopy Model	Kusaka et al. (2001), Chen et al. (2004)	3	3
SM2U	Soil Model for Submesoscales (Urbanized)	Dupont and Mestayer (2006), Dupont et al. (2006)	1	1
SNUUCM	Urban Canopy Model	Ryu et al. (2009)	1	1
SRUM2/SRUM4	Single Column Reading Urban Model tile version	Harman and Belcher (2006), Porson et al. (2009)	4	1
SUEB	Slab Urban Energy Balance Model	Fortuniak et al. (2004, 2005)	1	1
SUMM	Simple Urban Energy Balance Model for Mesoscale Simulation	Kanda et al. (2005a,b; 2007), Kawai et al. 2007, 2009)	1	1
TEB	Town Energy Balance	Masson (2000), Masson et al. (2002), Lemonsu et al. (2004)	1	1
TEB07	Town Energy Balance 7	Hamdi and Masson (2008)	1	1
TUF2D	Temperatures of Urban Facets 2D	Krayenhoff and Voogt (2007)	1	1
TUF3D	Temperatures of Urban Facets 3D	Krayenhoff and Voogt (2007)	1	1
VUCM	Vegetated Urban Canopy Model	Lee and Park (2008)	1	1

Grimmond et al. (2010, 2011) JAMC, IJC

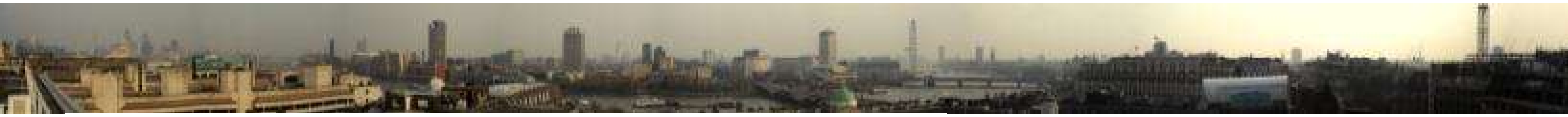
Evaluation with Vancouver Industrial Area observations

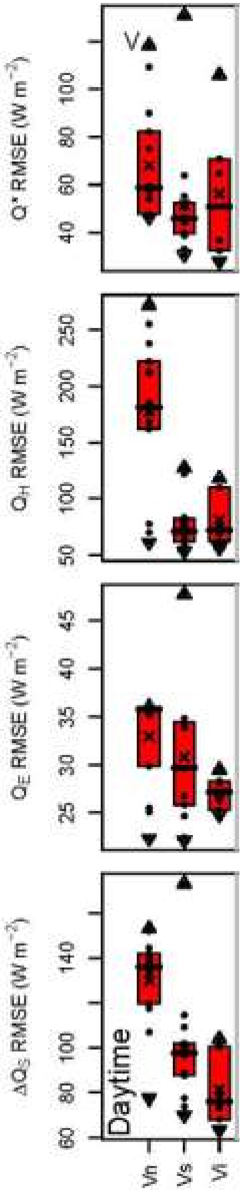
VL92: Ranked RMSE, All hours (N=312), Four Fluxes, 33 models



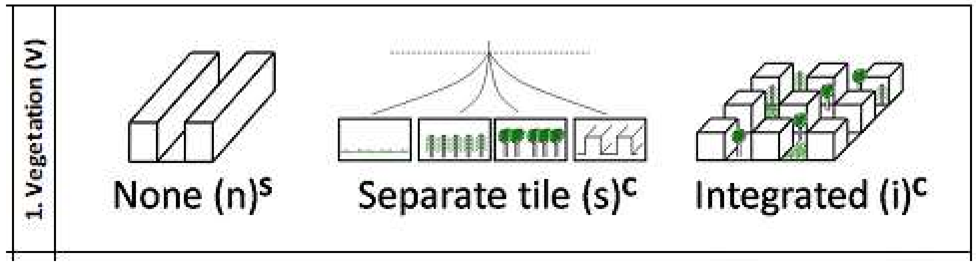
Grimmond et al. (2010) JAMC

Modelling Approach can be very important





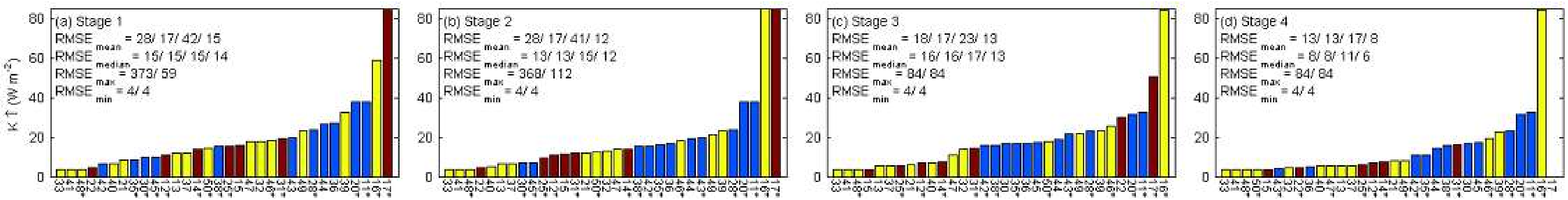
VL92 Model Classes, Daytime RMSE



Vegetation matters – for all fluxes
Even in an area with very little vegetation

Grimmond et al. (2010) JAMC

Amount information known about the surface is important



Phase 2 (Melbourne): Outgoing Shortwave Radiation

Increasing Information about the site →

Observations	Plan area fraction	Heights	Material characteristics
Latitude, Longitude (dummy)	(pervious, impervious)	Plan area fraction (Impervious⇒road/building)	Albedo, Thermal properties
1	2	3	4

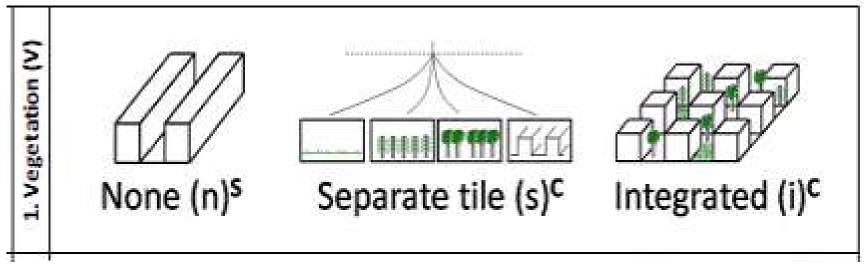
Yellow	Simple
Blue	Medium
Crimson	Complex

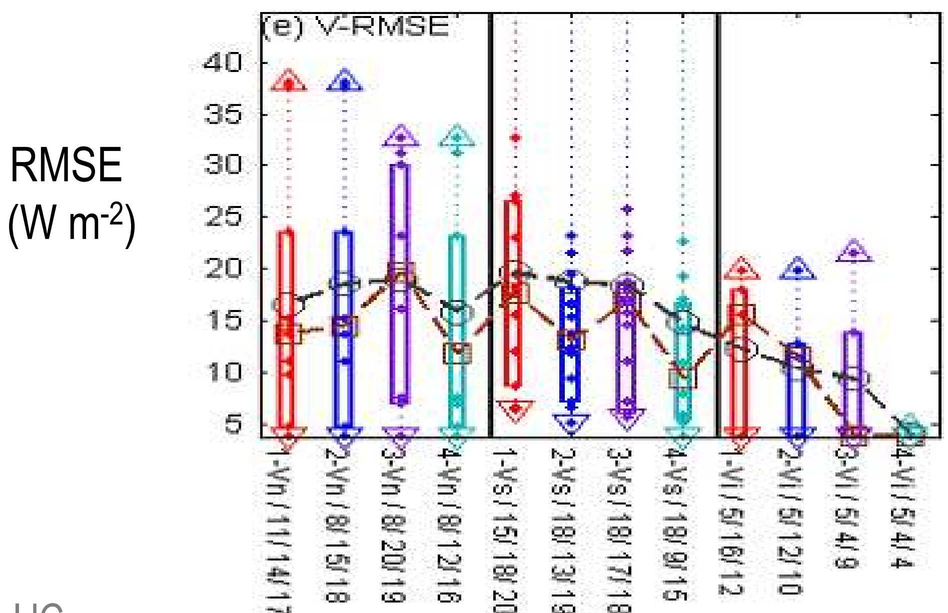
Grimmond et al. (2011) IJC

(Melbourne) : Outgoing Shortwave Radiation

Increasing Information about the site →

Observations Latitude, Longitude (dummy)	Plan area fraction (pervious, impervious)	Heights Plan area fraction (Impervious⇒road/building)	Material characteristics Radiative, Thermal properties, etc
1	2	3	4





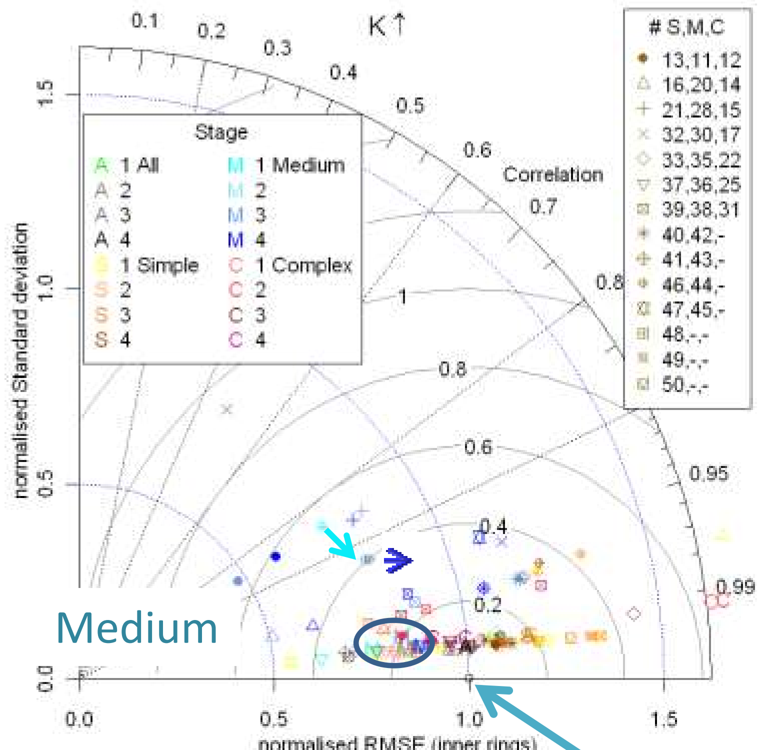
Cut off at 0.4 of maximum RMSE

Median ⊡ Mean ⊙ IQR

• Individual model RMSE

Grimmond et al. (2011) IJC

Phase 2: PILPS – Urban: K↑



Normalized
Standard Deviation

Correlation

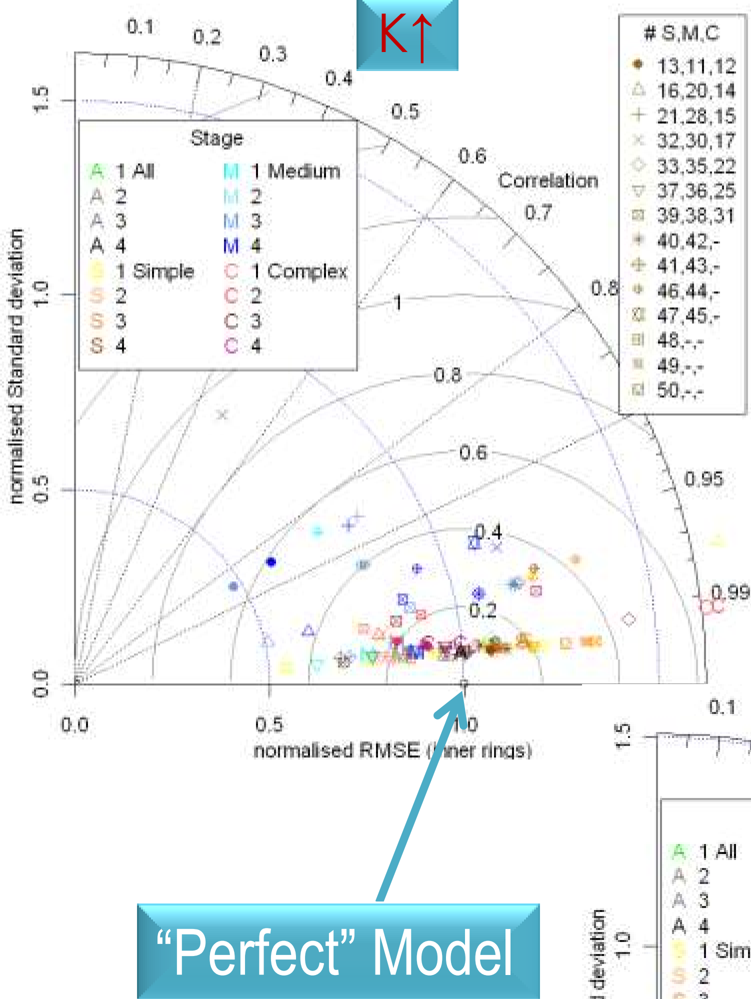
Normalized RMSE

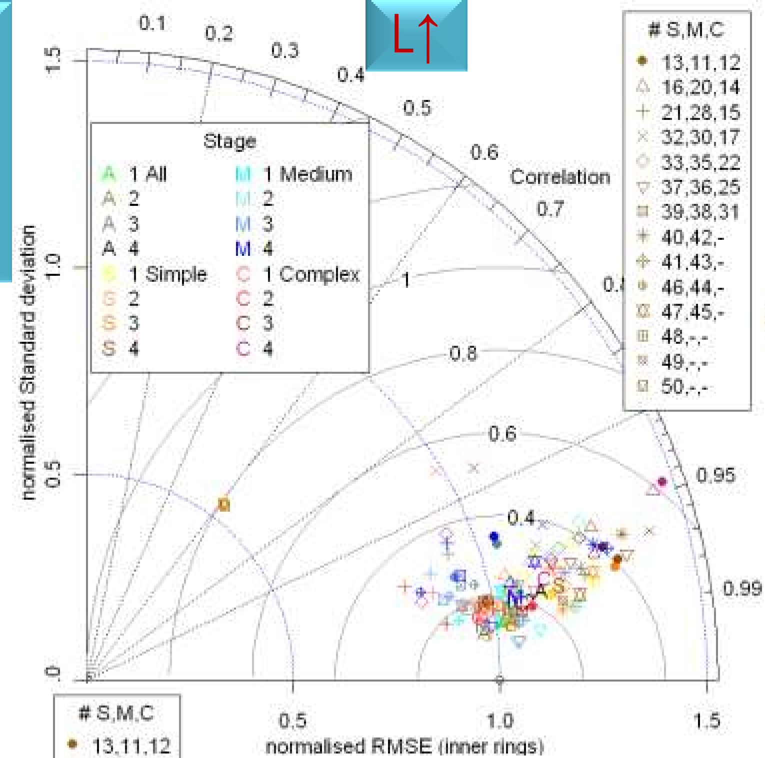
"Perfect" Model

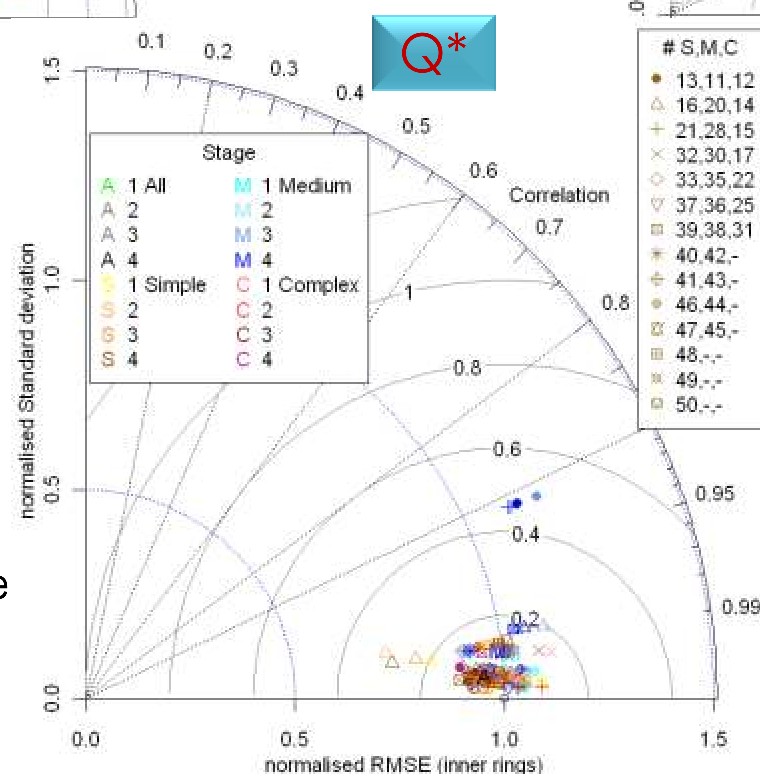
Symbols: individual models
1-4: increasing information about site
Letters: Ensemble model results

Grimmond et al. (2011) IJC

Overall Performance Radiation K↑, L↑, Q*







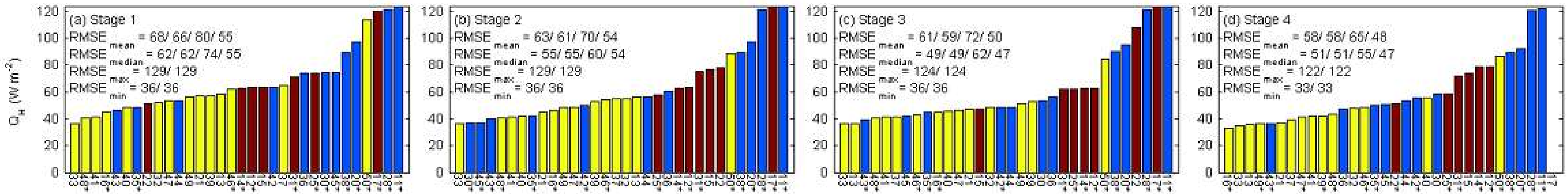
Symbols: individual models
Letters: Ensemble model results
1-4: increasing information about site

Phase 2: PILPS - Urban

Grimmond et al. (2011) IJC

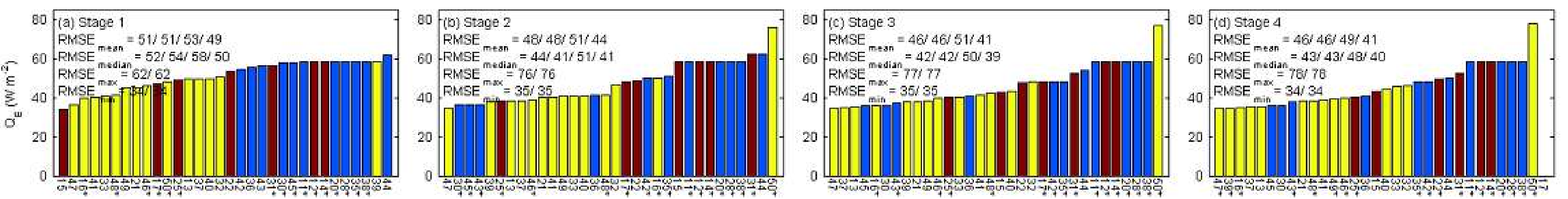
Melbourne: Turbulent Sensible Heat Flux

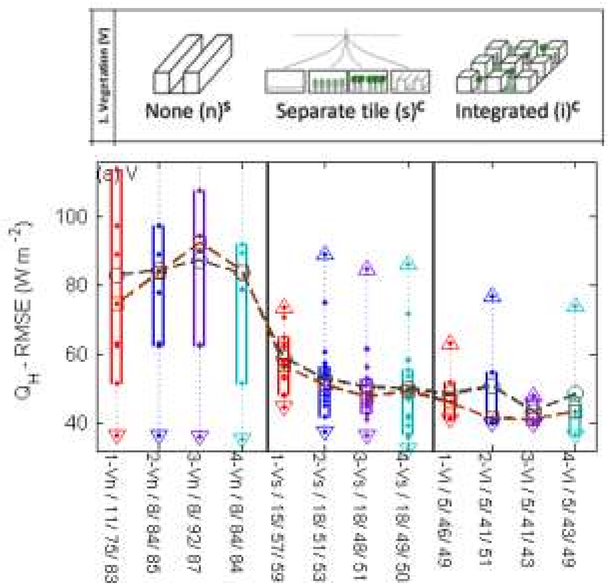
Mean Obs. Flux: 37.9 W m^{-2} All hours 12 months

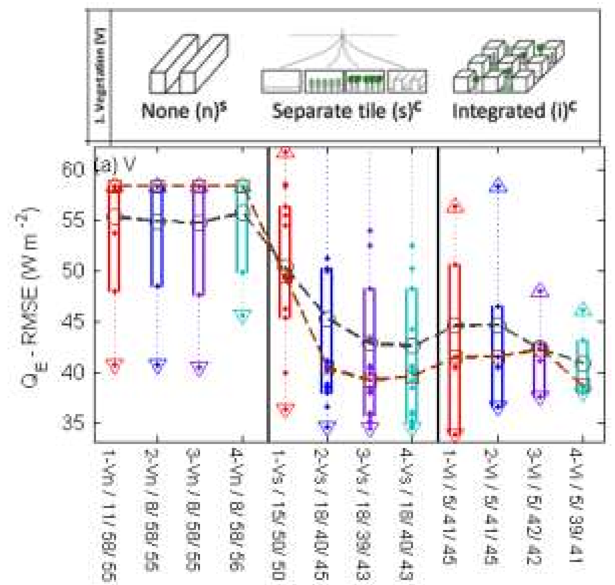


Turbulent Latent Heat Flux

Mean Obs. Flux: 32.5 W m^{-2}



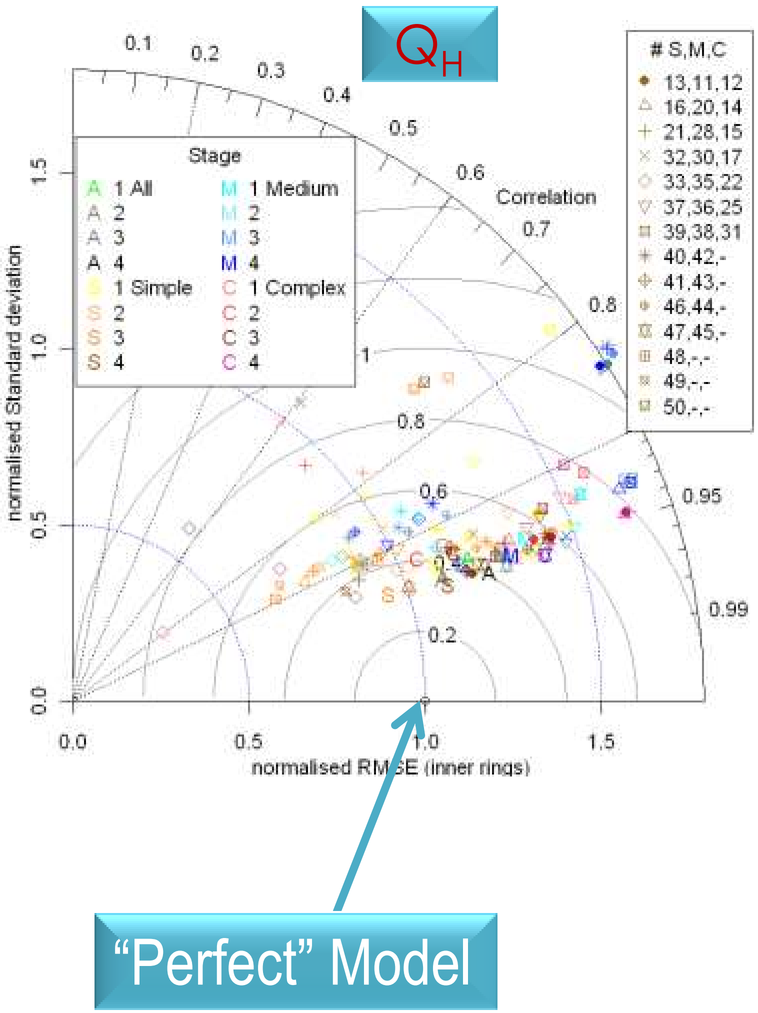


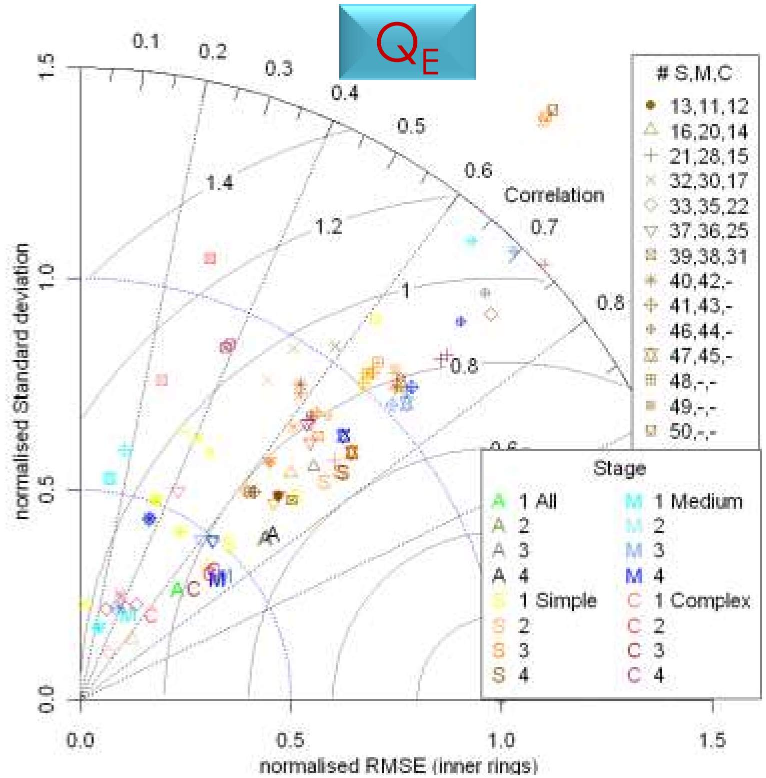


Yellow	Simple
Blue	Medium
Crimson	Complex

Grimmond et al. (2011) IJC

Overall performance: Q_H, Q_E Phase 2: PILPS- Urban



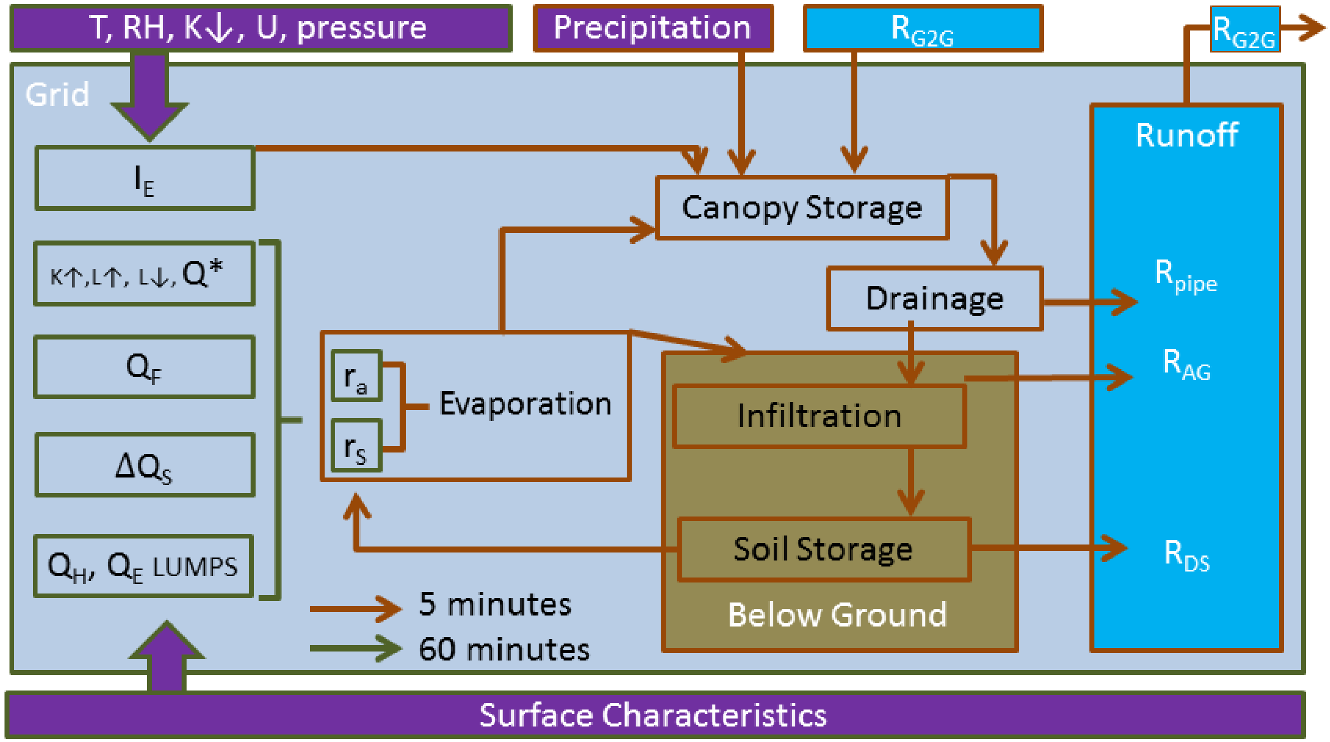


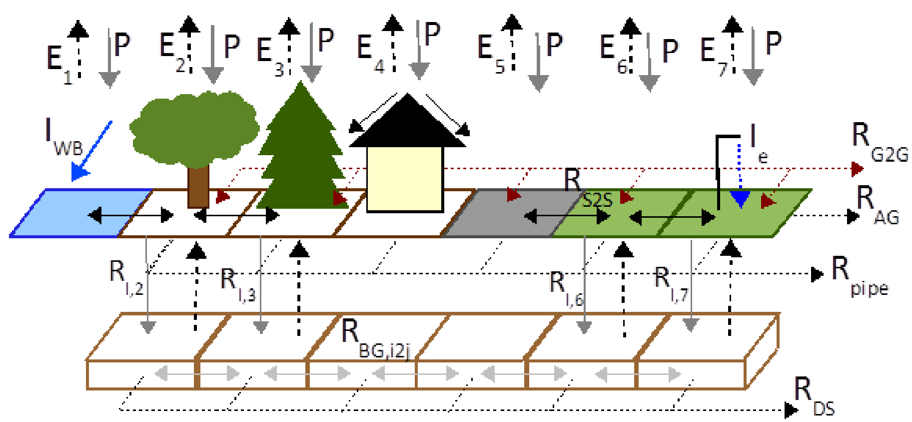
Grimmond et al. (2011) IJC

Symbols: individual models
Letters: Ensemble model results
1-4: increasing information about site

SUEWS: Surface Urban Energy and Water Balance Scheme

- Local scale model
- Links to create catchment and/or to meso-scale model





Järvi et al. (2011) J. Hydrology

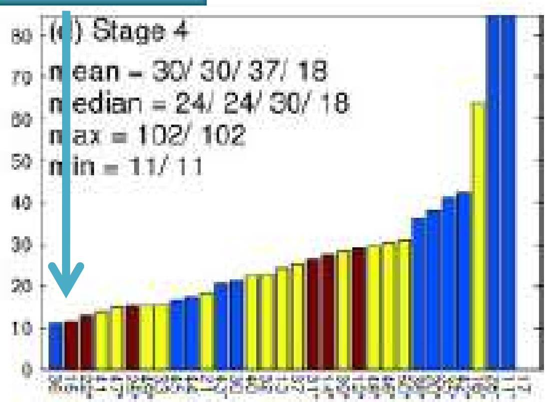
International urban energy balance comparison

SUEWS – did not participate

Arrows indicate relative performance

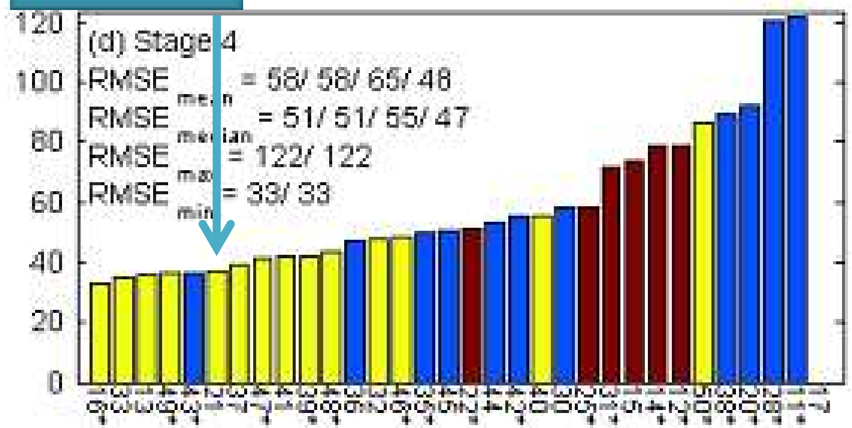
Q*

12.0 W m-2



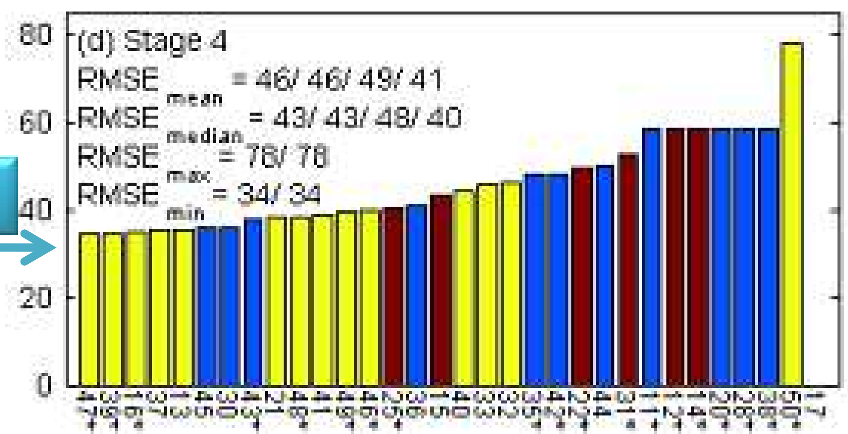
Q_H

38.4 W m-2



Q_E

31.7 W m-2

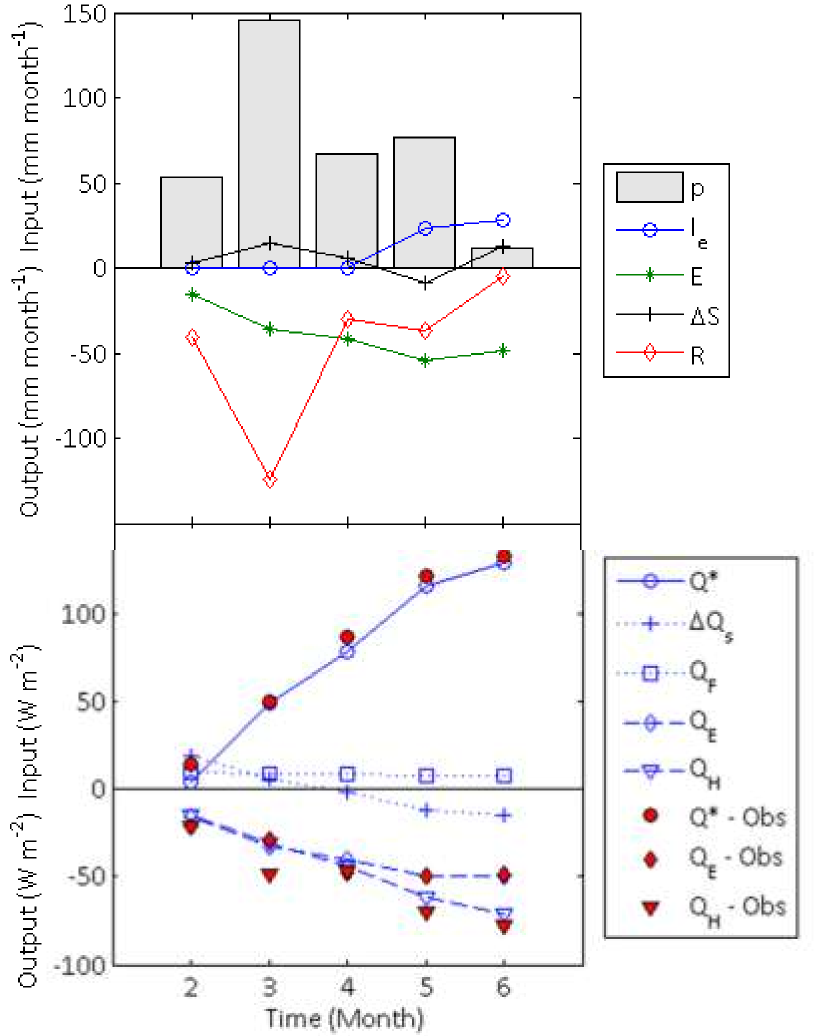


Järvi and Grimmond

VS87: Monthly Energy and Water Balance Fluxes

Water Balance

Energy Balance



Järvi et al. (2011) J. Hydrology