A multi-layer urban canopy model for neighbourhoods with trees

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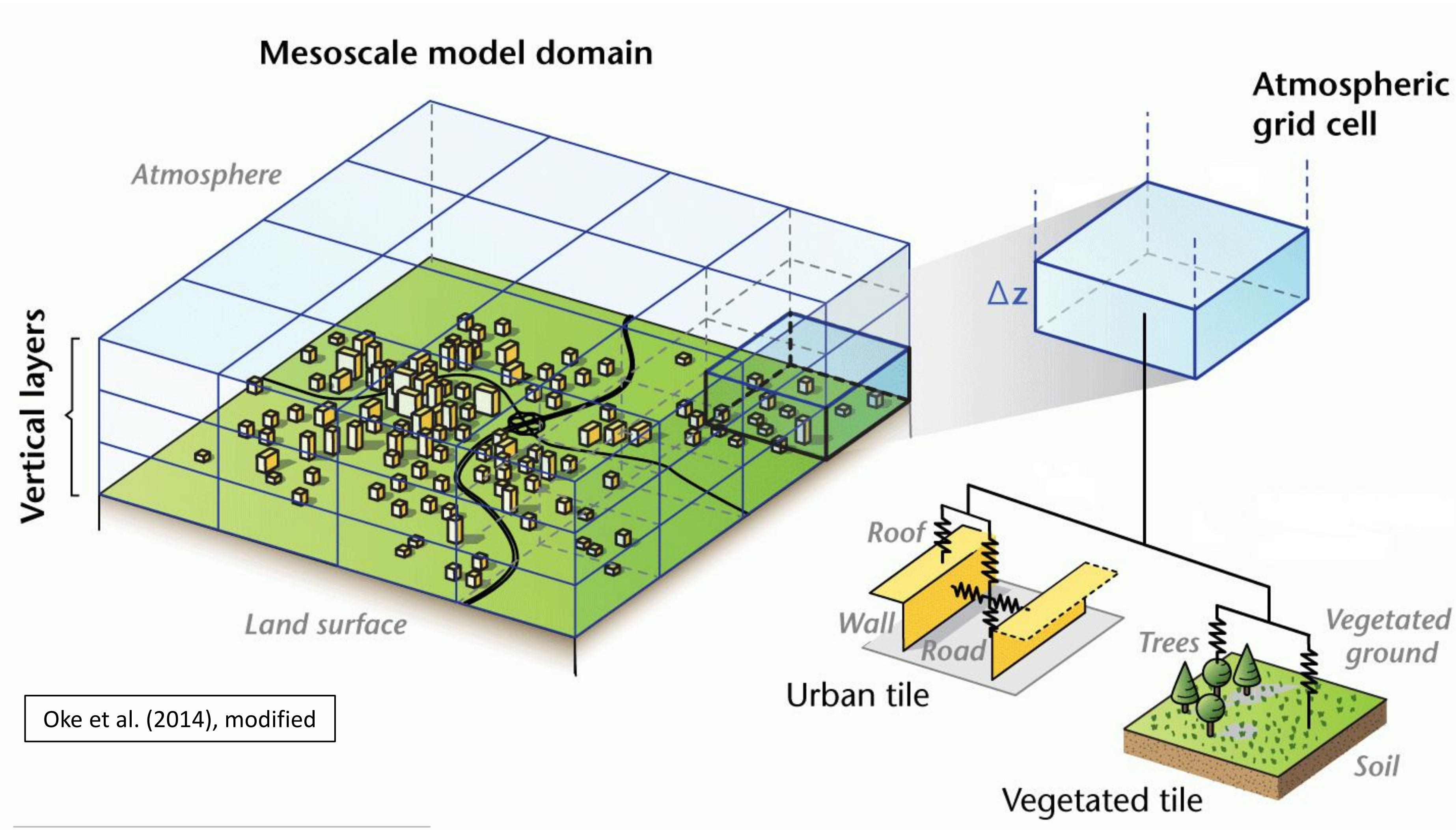
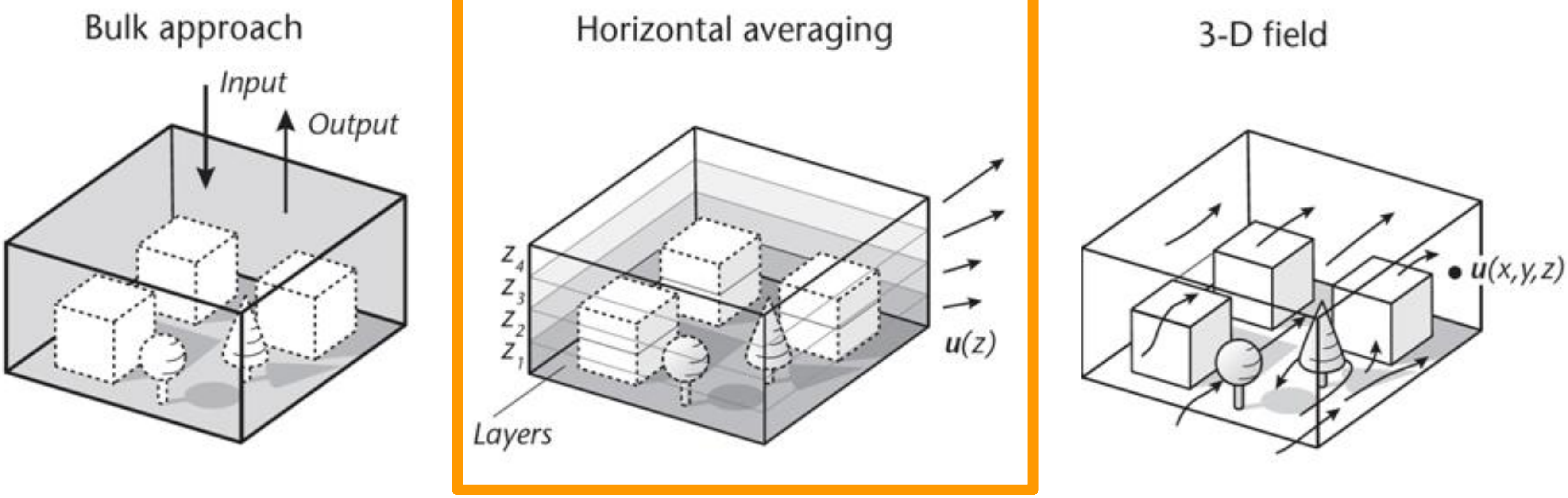
Mesoscale atmospheric modelling



Averaging scale and dimension

Multi-layer urban canopy model

Oke et al. (2014), modified



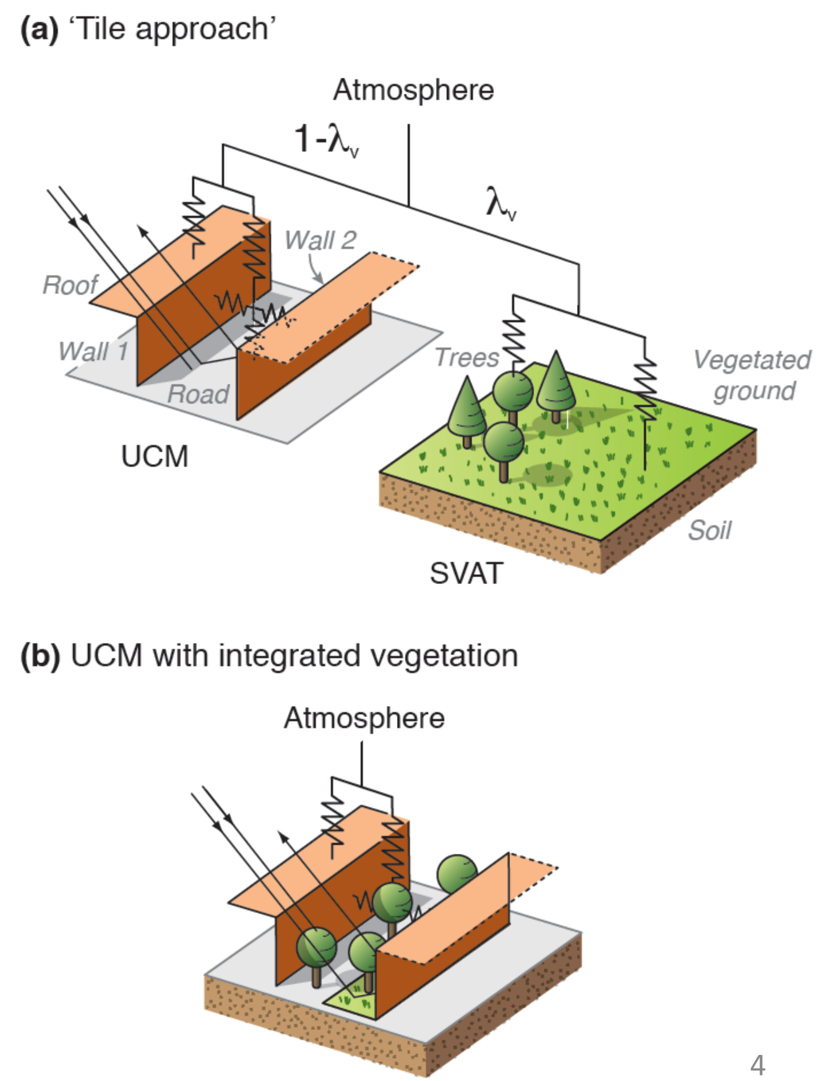
More process-based & less parameterized

Lower computational cost

Tree-building interaction

Trees and buildings interact

- Radiatively:
  - Solar shading
  - Longwave trapping
  - Multiple reflection
- Dynamically:
  - Sheltering
  - Mutual impacts on turbulent environment



Objectives

Model Development

1. Numerical model for the impacts of trees on neighbourhood-average *radiation* exchange (Krayenhoff et al. 2014 BLM)

2. Parameterization for the impact of trees on neighbourhood-average *flow* (Krayenhoff et al. 2015 BLM)

3. ***Urban Canopy Model*** **(UCM) for neighbourhoods with trees (includes models *1* and *2)***

- Multi-layer
- Process-based
- Computationally-efficient
- Explicitly account for building-tree interaction

Objective 1

Numerical model for the impacts of trees on neighbourhood-average *radiation* exchange

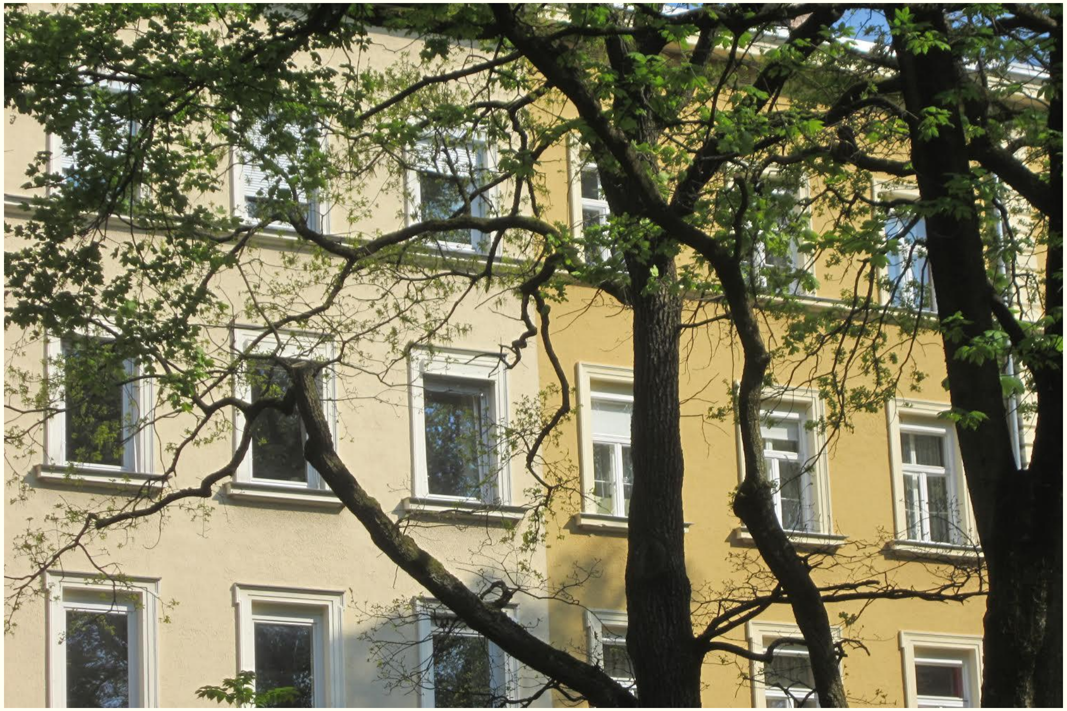
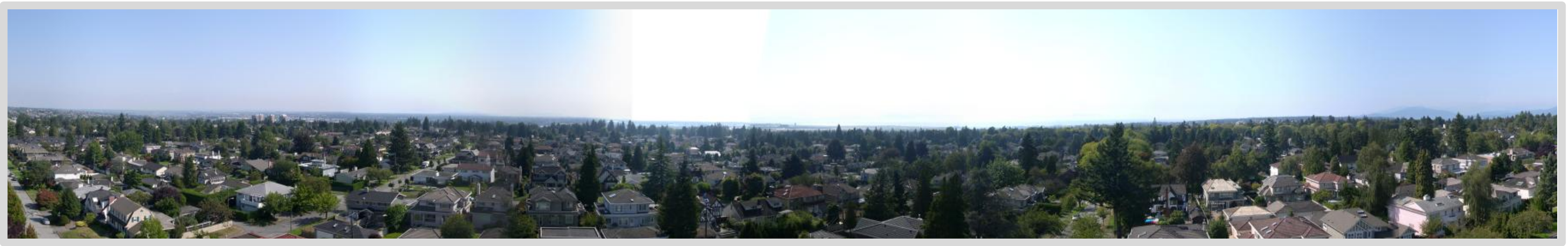
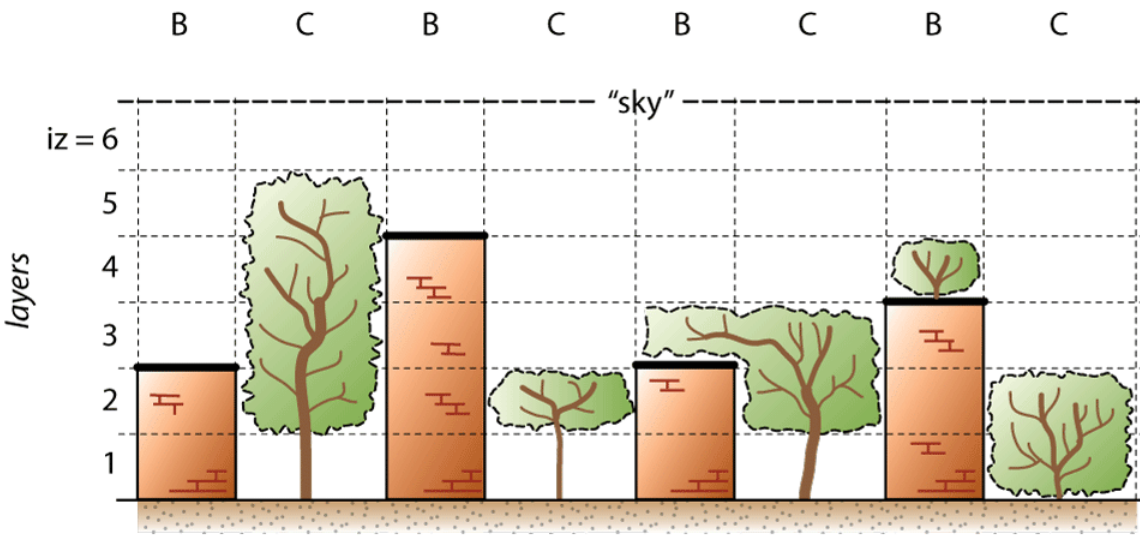


Photo: Andreas Christen

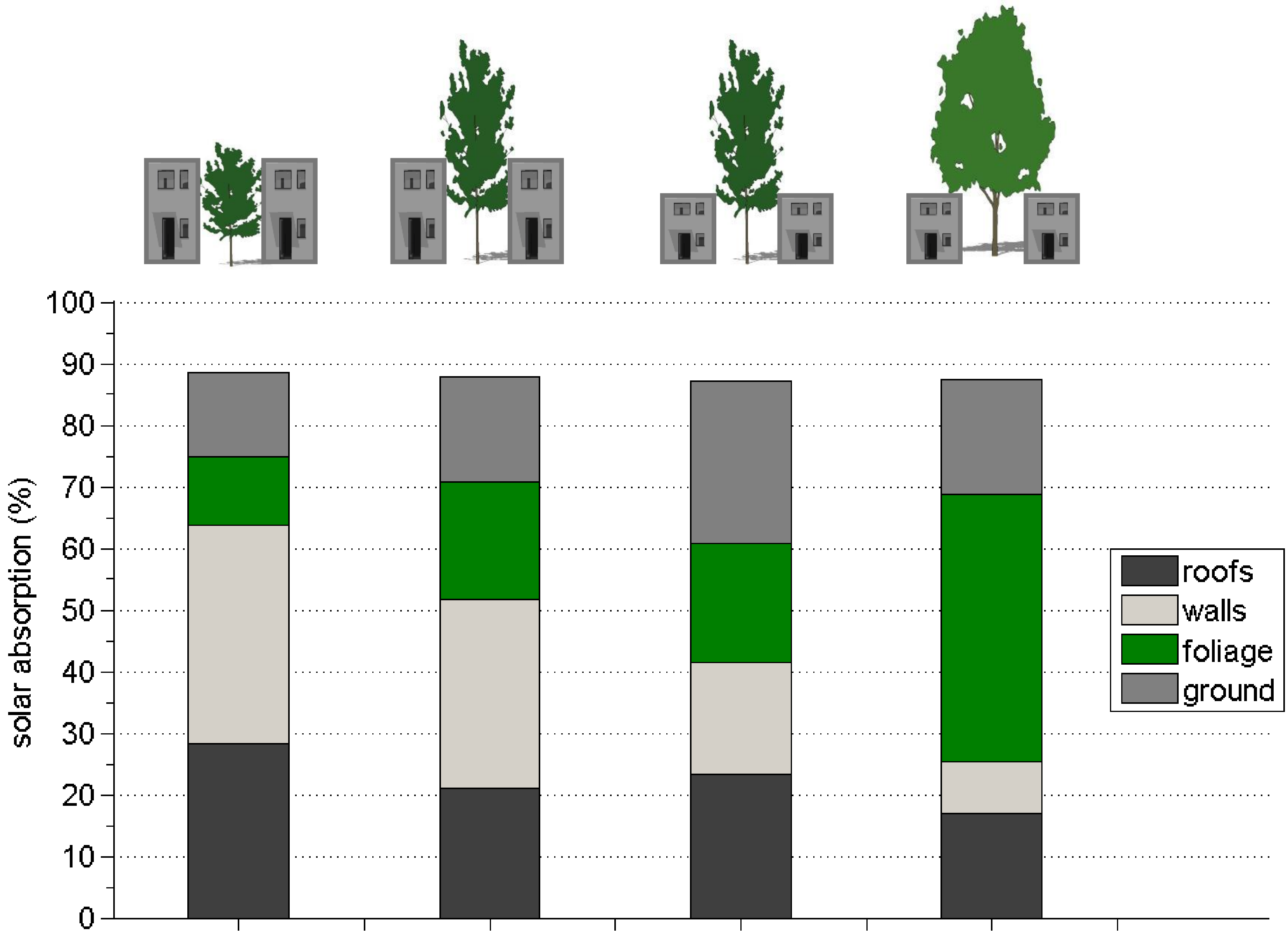
Radiation model: Conceptualization & physics





- Tree foliage is evenly distributed across the 'canyon' or 'building' spaces
- Beer's law for attenuation by vegetation; spherical leaf angle distribution with *clumping*
- Ray tracing, view factors, and matrix inversion

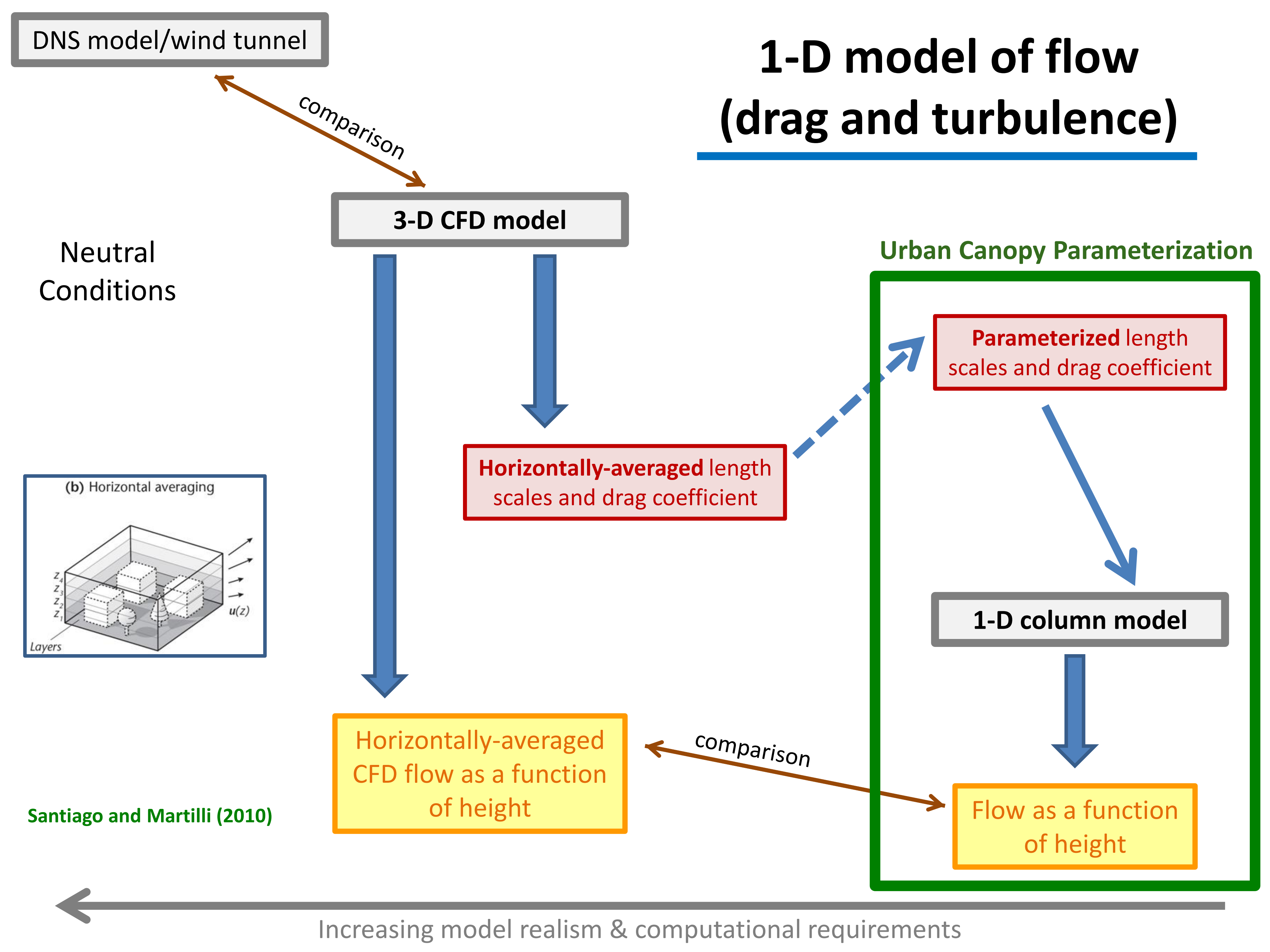
Solar absorption by surface type



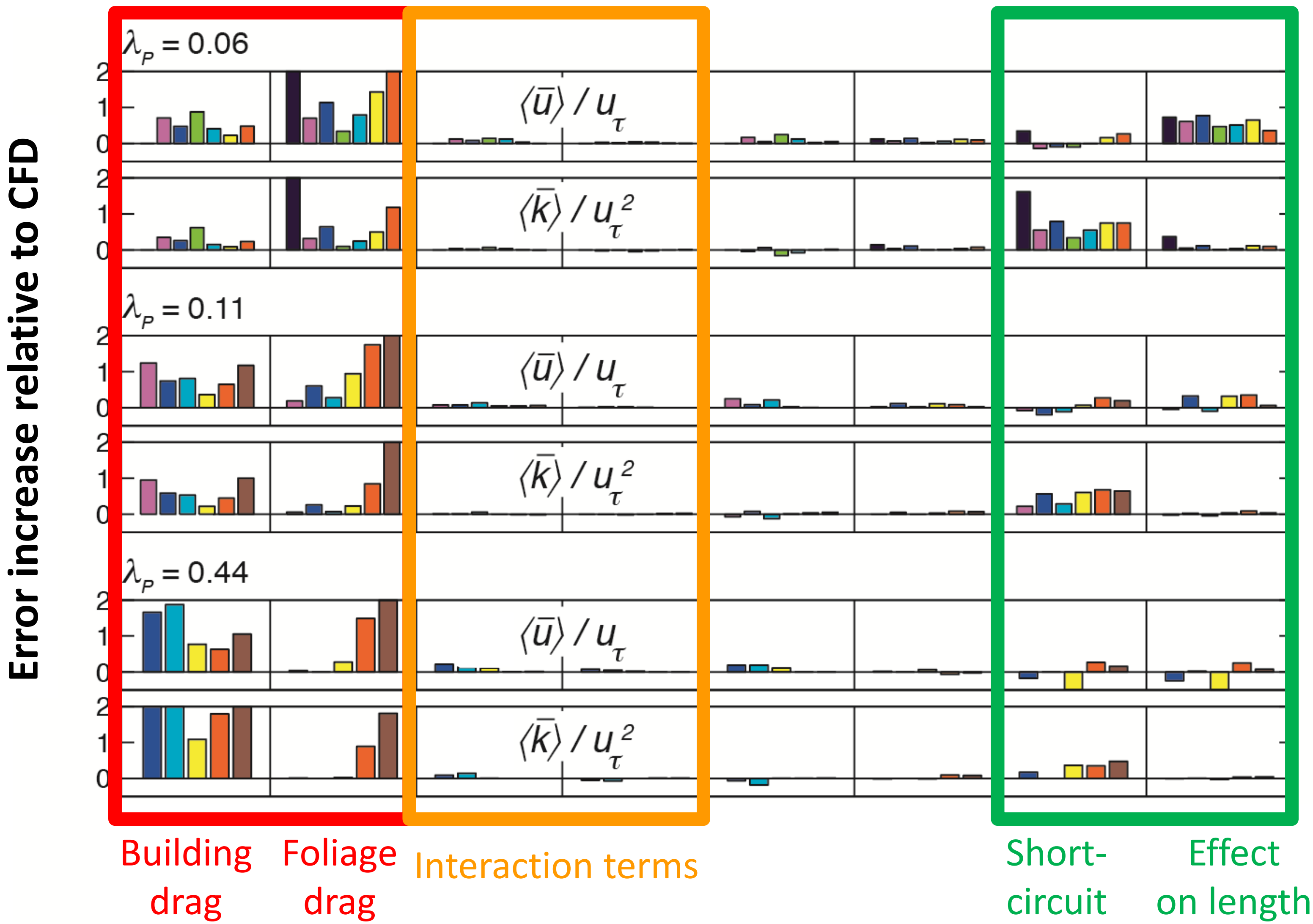
Objective 2

Parameterization for the impact of trees on neighbourhood-average *flow*

Photo: Andreas Christen


1-D model of flow
(drag and turbulence)
DNS model/wind tunnel
comparison
3-D CFD model
Neutral
Conditions
(b) Horizontal averaging
z_4
z_3
z_2
z_1
$u(z)$
Layers
Horizontally-averaged length scales and drag coefficient
Horizontally-averaged CFD flow as a function of height
Santiago and Martilli (2010)
Urban Canopy Parameterization
Parameterized length scales and drag coefficient
1-D column model
Flow as a function of height
comparison
Increasing model realism & computational requirements

Removal of each source/sink term in 1-D model



u = wind

k = turbulent kinetic energy

Objective 3

BEP-Tree: An *Urban Canopy Model* for neighbourhoods with trees

Photo: Iain Stewart

Multi-layer urban canopy model with trees

Radiation and surface energy balance

Multi-layer urban radiation model with trees
-Shortwave direct & diffuse
-Longwave
(*Krayenhoff et al. 2014*)

+

BEP multi-layer urban canopy model (part)
$Q^* = Q_H + Q_G$ (facets)
(*Martilli et al. 2002*)

+

Foliage energy balance
$Q^* = Q_H + Q_E$
(*Campbell and Norman 1998*)

+

Dynamics: drag and turbulence

1-D column turbulent diffusion model with source terms of building impacts on flow
-wind & TKE prognostic equations
(*Santiago and Martilli, 2010*)

Parameterization of tree impacts on flow
-source/sink terms in wind & TKE equations
(*Krayenhoff et al. 2015*)

+
-temperature & specific humidity equations
-turbulent Prandtl number (*Pr*)
-buoyant production of TKE

+
-thermal effects on turbulent length scales
(derived from *Santiago et al. 2014*)

BEP-Tree

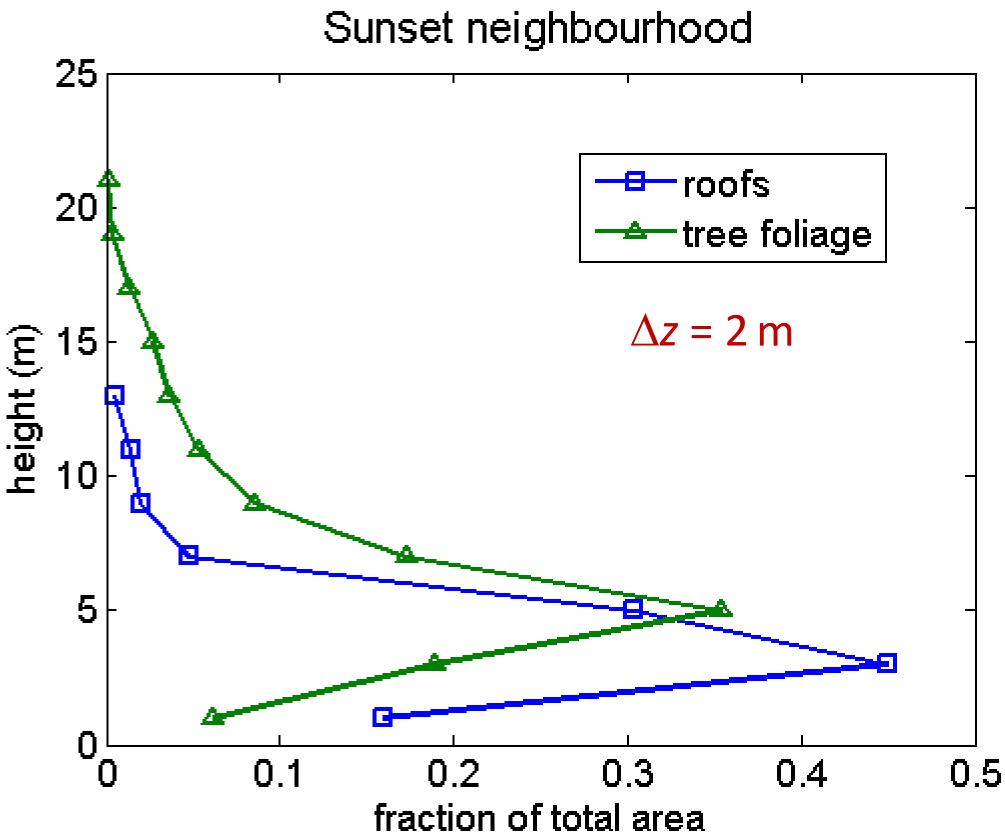
Model testing – Vancouver Sunset

View from tower, July 20, 2008

Building area fraction
$0.29\ m^2\ m^{-2}$

Leaf area index
$0.39\ m^2\ m^{-2}$

Model inputs



Foliage clumping:
Ω= 0.34

Turbulent Prandtl number:
Pr = 0.25

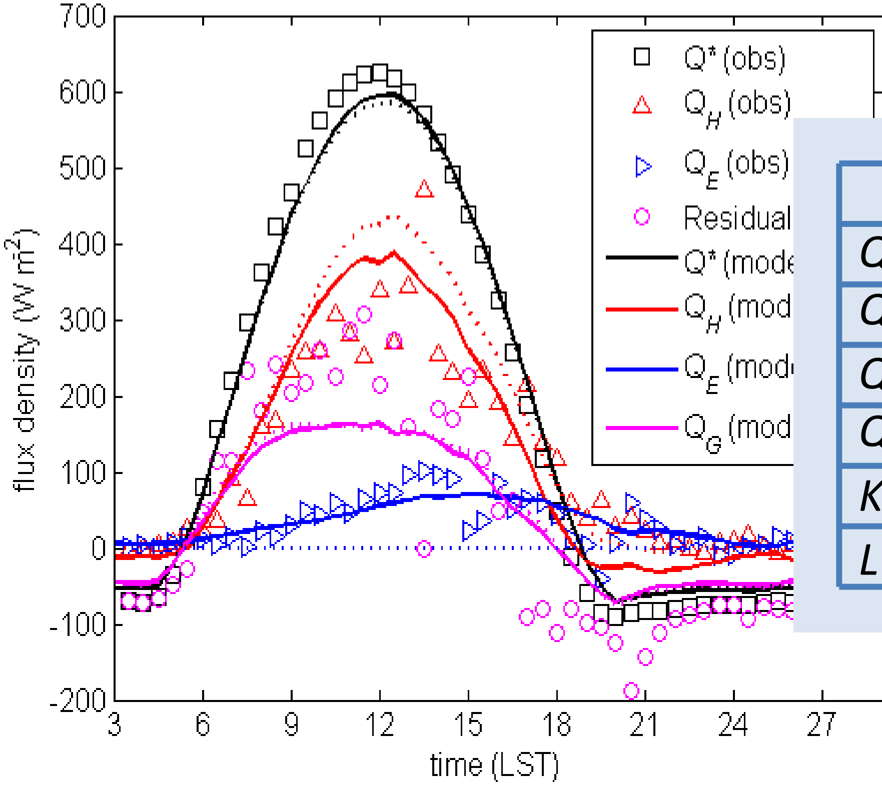
Two street directions: 0°, 90°

Radiation/thermal parameters from LCZ 6: Open Low-rise (Stewart et al. 2014) and Krayenhoff and Voogt (2010)

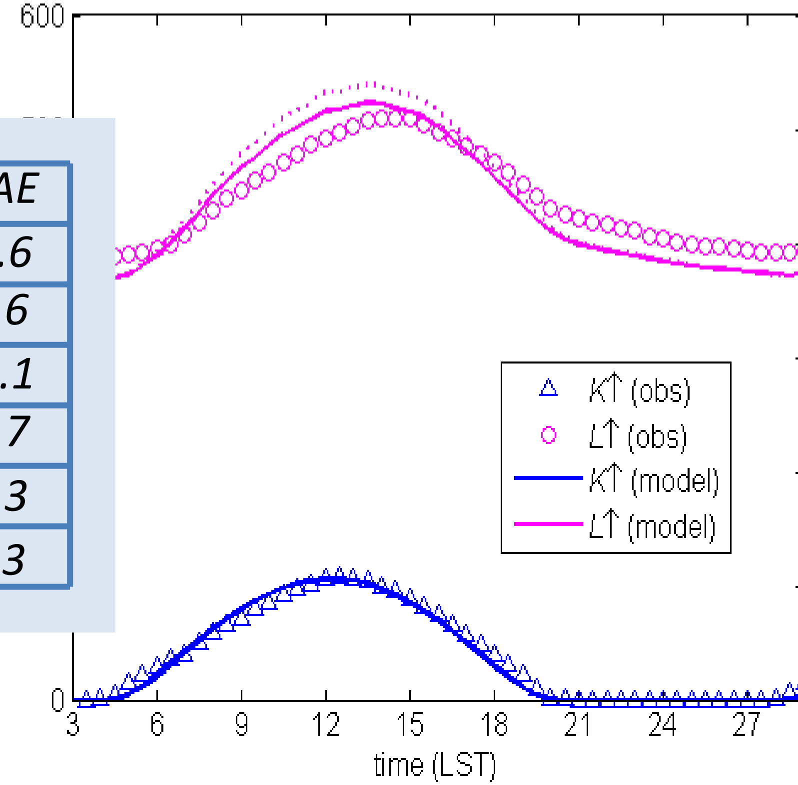
- *Albedos*
- *Emissivities*
- *Thermal conductivities*
- *Heat capacities*
- *Thicknesses*

Sunset: July 20, 2008 (dry summer)

Overall energy exchange



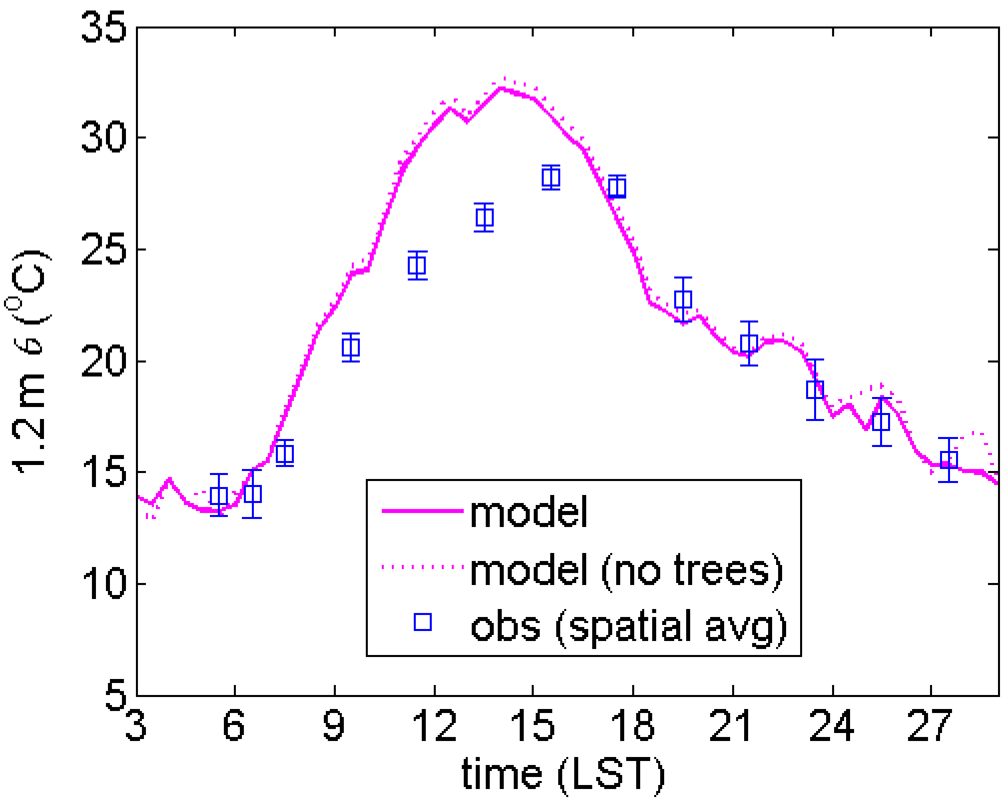
Upward radiation fluxes



	MAE
*Q**	*23.6*
Q_H	*41.6*
Q_E	*15.1*
Q_G	*58.7*
K↑	*3.3*
L↑	*16.3*

Note: Grass contributes minimal Q_E

Sunset: Sept. 7, 2011



Lower canopy air temperature from *detailed spatial sampling* over ≈4 km^2

(Crawford and Christen, 2014)

Effects of trees on canopy thermal environment

1. Cooling: shading of canopy surfaces from **shortwave radiation**
2. Heating: trapping of **longwave radiation** within canopy
3. Heating: reduction of **wind** and **turbulence** (venting) in canopy

$$\left.\begin{array}{l}1.\\2.\end{array}\right\} \Omega_{rad} \qquad 3.\ \} \ \Omega_{dyn}$$

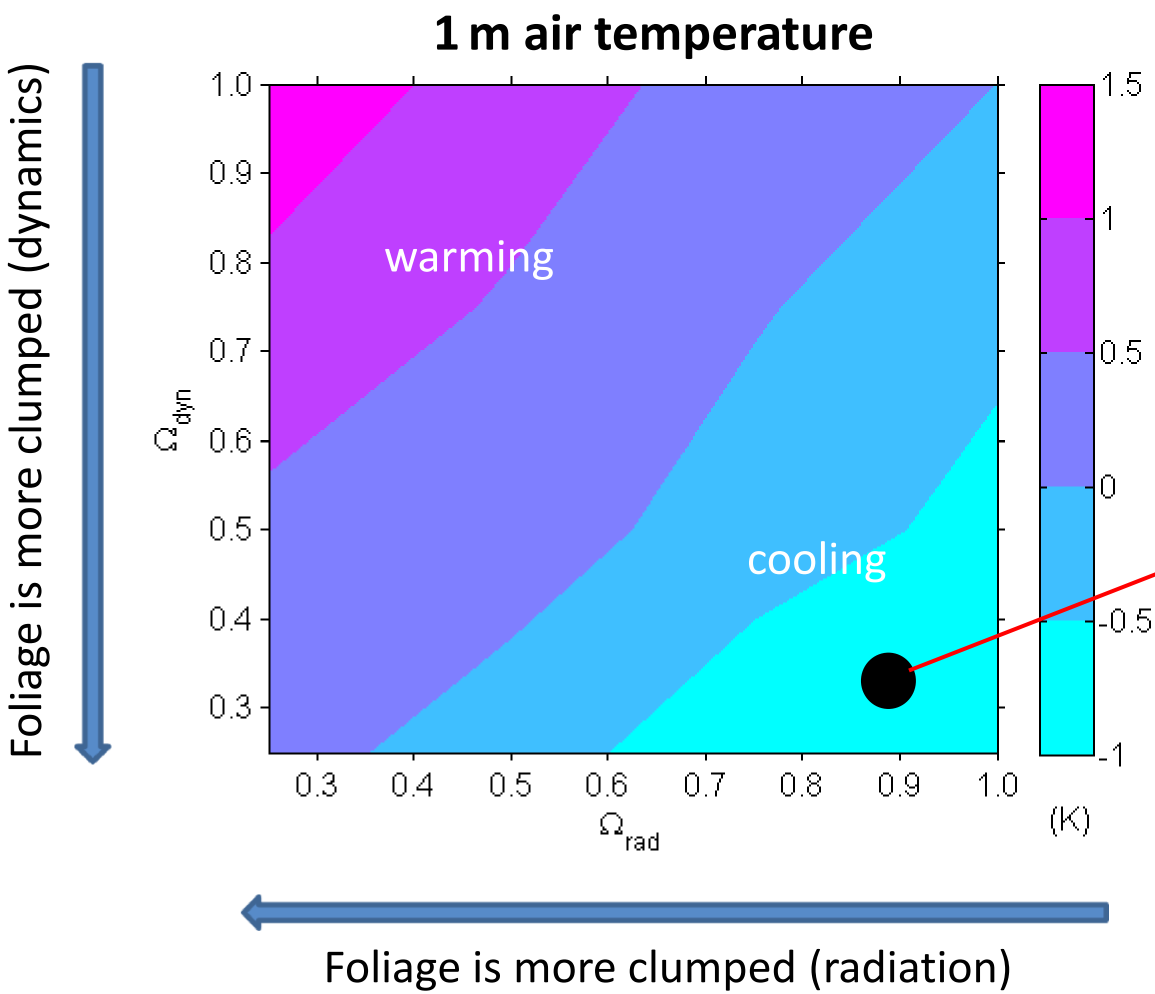
In radiation transfer through tree canopy, clumping of foliage (Ω_{rad}) increases transmission

Ω_{rad} = 1 means random foliage distribution (~minimum transmission)
Ω_{rad} = 0 means all leaves are at the same point in space (maximum transmission)

Marcolla et al. (2003) define an analogous clumping coefficient for the dynamic sink and source terms, Ω_{dyn}, which assumes shaded leaves do not contribute to momentum absorption

-> *effective leaf area density for dynamic source/sink terms*

Effects of trees on canopy thermal environment



Vancouver Sunset

1500 LST
July 20, 2008

Radiation: Sub-crown scale
Dynamics: All scales

Foliage-induced drag and dissipation of turbulence are too strong in the model (due to homogeneous leaf distribution)?

Summary: Urban Canopy Model with Trees

- BEP-Tree:
  - First multi-layer UCM to integrate trees & building-tree interactions
- Urban trees:
  - Add latent heat at the expense of sensible heat
  - Have both warming (e.g., reduced wind and turbulence) and cooling (e.g. solar shading) effects on the canopy at the neighbourhood scale
- Future work
  - ***Canopy* measurements needed in *neighbourhoods with trees* for model evaluation: fluxes, surface temperatures**
  - Foliage clumping at neighbourhood scale for radiation, dynamics?
  - Canopy venting too low: Dispersive fluxes? Thermal effects?
  - Model development: Stomatal conductance, Hydrology, Building energy

Thank you

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