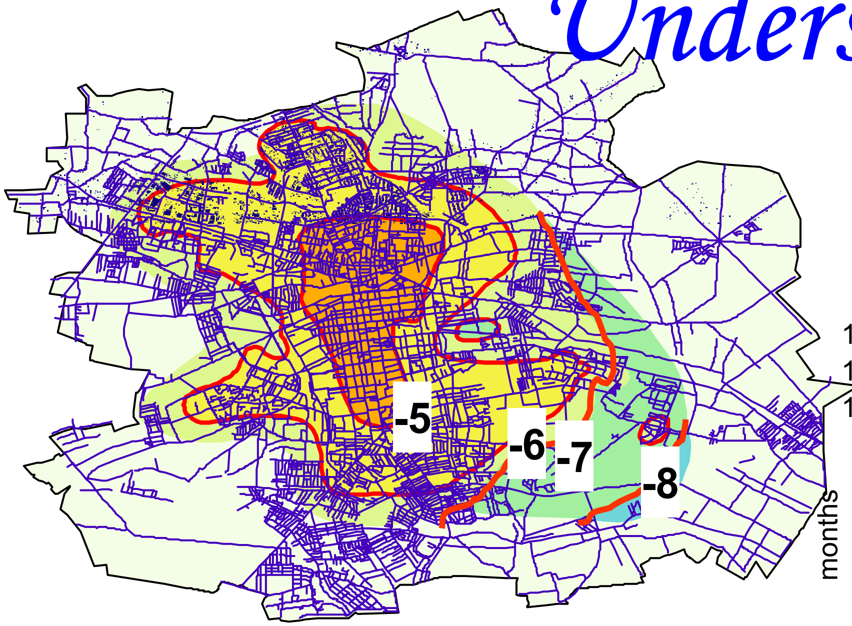
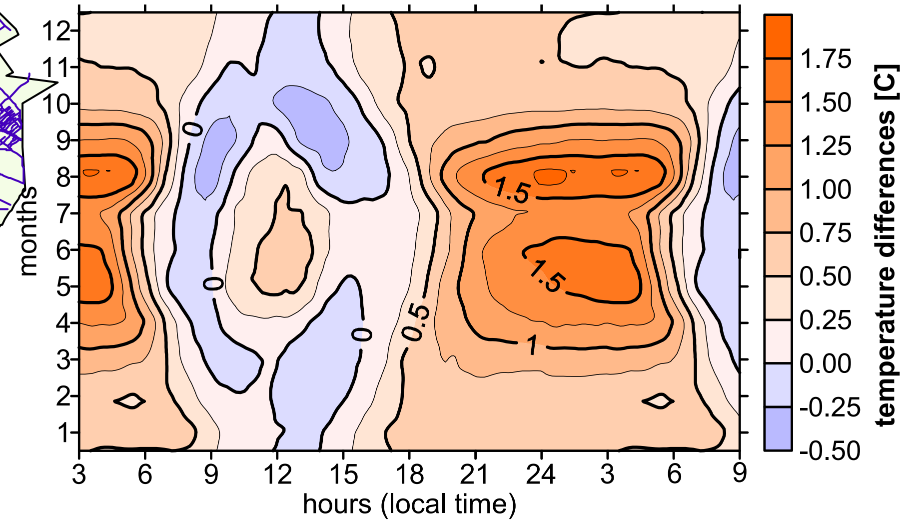
** Sources of figures given at end – none should be used without attribution

"The Continuing Quest to Understand Urban Heat Islands"





UHI in Lodz, Fortuniak, 2007

Tim Oke

Emeritus Professor

University of British Columbia

Vancouver, Canada

Hong Kong Workshop, May 2008

Common sources of UHI misunderstanding

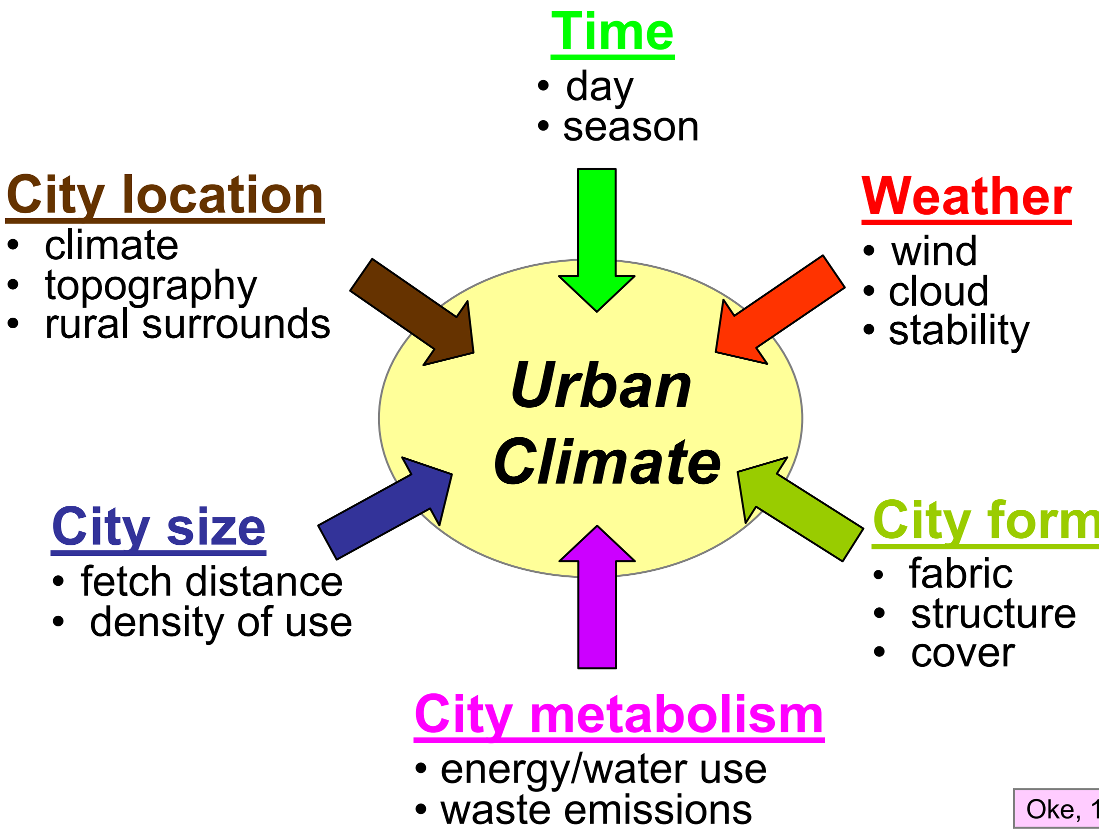
Failure to recognize significance of scale that sets:

- source areas for each UHI
- process mix for each UHI
- mix of controls affecting each UHI
- conceptual frameworks to model each type
- ‘target’ phenomena of different users (e.g. pedestrian climate, indoor climate, building climate, city-wide mitigation, photochemical plume)

Common experimental muddles and errors:

- representativeness of sites
- ‘urban-rural pairs’ paradigm -*Iain Stewart*
- limitations of techniques (time & space sampling, instrument FOV, emissivity, etc) - *James Voogt*
- mixing together scales of observation, modeling
- poor experimental control (wind/cloud, frontal passage)

Controls on urban climate effects (incl. UHI)



Oke, 1980, unpubl.

'Fixed' – Location **'Modulators'** – Time, Weather
'Manageable' (policy, planning, design) – Size, Form, Metabolism

Climatically-significant changes due to urbanization

Air changes:

- ***pollutants*** – gases and particulates
- ***emissions*** - ‘waste’ heat, water vapour

Surface changes:

- ***urban structure*** – size, shape, spacing, arrangement of buildings & trees
- ***cover*** – built-up, paved, bare, water
- ***fabric*** – properties of building & natural materials,
- ***metabolism*** – human generated heat, water and pollutants

Urban climate effects are ‘caused’ by urban-rural differences in surface properties:

- ***roughness*** – roughness length (z_0), displacement length (z_d)
- ***radiation*** – albedo (α), emissivity (ε), surface temperature (T_0)
- ***moisture*** – surface wetness, soil moisture
- ***thermal*** – admittance (μ) [conductivity, heat capacity, diffusivity]
- ***metabolism*** – anthropogenic heat (Q_F), water (combustion ***F***, irrigation ***I***), pollutants [aerosols, gases]

These tend to cluster in classes giving typical districts with similar ability to modify the local climate – ***Urban Climate Zones (UCZ)*** – giving intra-urban variations

Urban Climate Zones (UCZ)

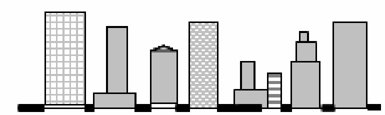
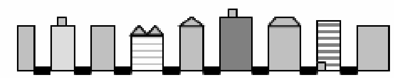
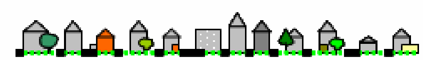
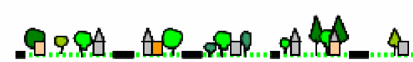
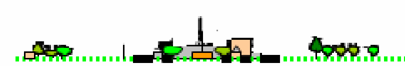
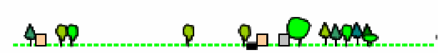
UCZ are 'homogeneous' urban districts of climatically-relevant properties (not land use) at local scale

Essential controls on urban climate impacts (*structure, cover, fabric, metabolism)* cluster. UCZ are easy to classify by visual images and 3 simple measures related to wind, thermal and moisture impacts:

Roughness: Davenport *et al.*, 2000 (wind & turbulence)

Aspect ratio: z_H/W
(flow regime & thermal)

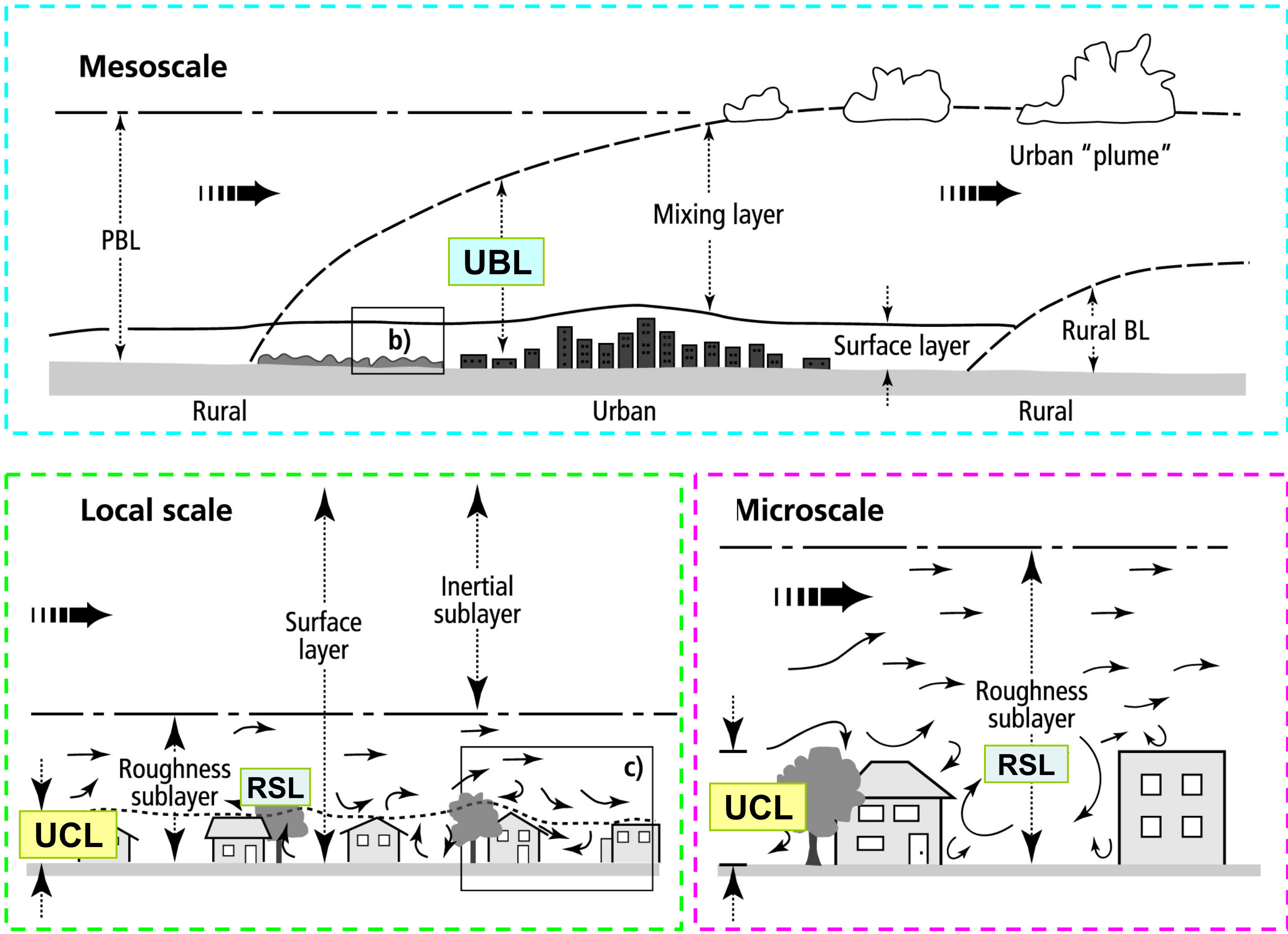
% Built: λ_B
Plan fraction built over (moisture & thermal), mostly sealed

Urban Climate Zone, UCZ[1]	Image	Roughness class[2]	Aspect ratio[3]	% Built (impermeable)[4]
1. *Intensely developed urban with detached close-set high-rise buildings with cladding, e.g. downtown towers*		8	> 2	> 90
2. *Intensely developed high density urban with 2 – 5 storey, attached or very close-set buildings often of brick or stone, e.g. old city core*		7	1.0 – 2.5	> 85
3. *Highly developed, medium density urban with row or detached but close-set houses, stores & apartments e.g. urban housing*		7	0.5 – 1.5	70 - 85
4. *Highly developed, low or medium density urban with large low buildings & paved parking, e.g. shopping mall, warehouses*		5	0.05 – 0.2	70 - 95
5. *Medium development, low density suburban with 1 or 2 storey houses, e.g. suburban housing*		6	0.2 – 0.6, up to >1 with trees	35 - 65
6. *Mixed use with large buildings in open landscape, e.g. institutions such as hospital, university, airport*		5	0.1 – 0.5, depends on trees	< 40
7. *Semi-rural development, scattered houses in natural or agricultural area, e.g. farms, estates*		4	> 0.05, depends on trees	< 10

Key to image symbols: buildings; vegetation; impervious ground; pervious ground

Oke, 2004

Scales and Layers Relevant to Urban Climate



Modified after Oke (1997)

Scales and Layers Relevant to Urban Climate

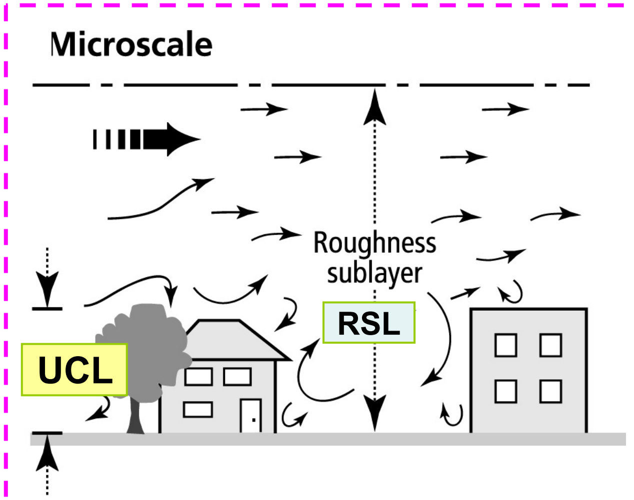
(a) Microscale – every surface and object has unique microclimate. Surface and air temperatures vary several degrees in short distances, airflow greatly perturbed by even small objects. Scales are the dimensions of individual buildings, trees, roads, streets, courtyards, gardens, etc. - from less than one to hundreds of metres

Source area - UCL T_a measurement is dominated by immediate surfaces, no greater than 0.5 km away

Processes – mainly wall, ground radiative (Q^*), conductive (Q_G) & convective sensible (Q_H) heat fluxes

Controls – fabric, structure, ground cover, metabolism, weather, time of day/season

Applications – pedestrian bioclimate, building & indoor climate, design

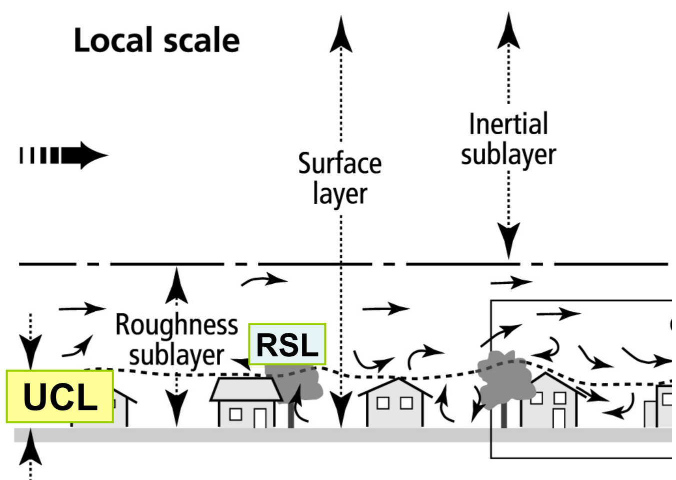


Modified after Oke (1997)

Scales and Layers Relevant to Urban Climate

(b) Local scale – standard climate stations are designed to monitor. Includes effects such as topography but excludes microscale. In cities this means the climate of neighbourhoods with similar urban development (surface cover, size and spacing of buildings, activity – *Urban Climate Zones UCZ*).

Source area - Signals are an integration of the mix of microclimatic effects of the UCZ source area. Typical scales one to several km. For representative UCZ T_a measurement either from truly representative UCL station or better at top of the RSL where turbulent mixing has blended microscale effects



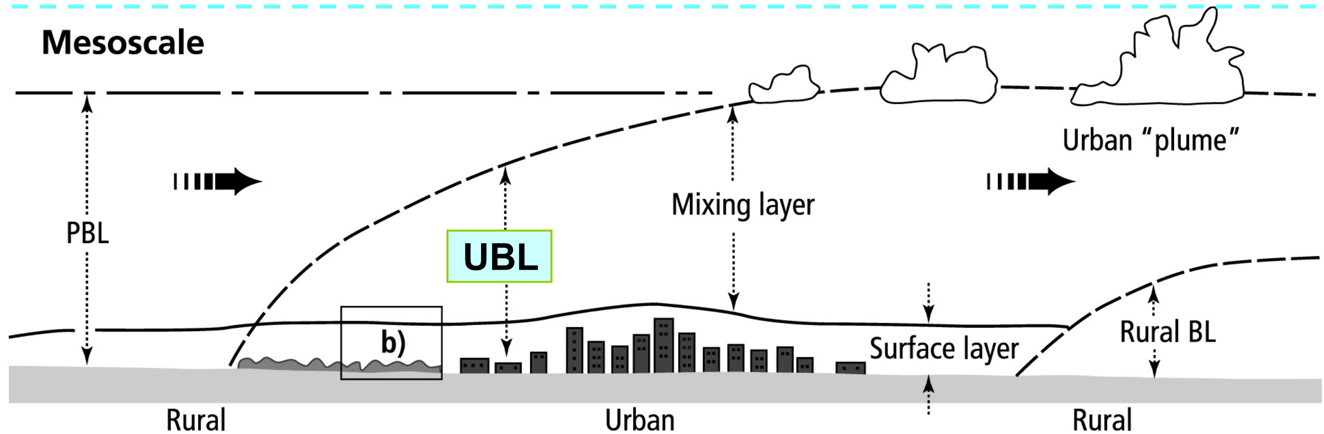
Processes – heat fluxes from roofs, chimneys and UCL top, i.e. spatial average of UCZ surface-air volume

Controls – UCZ class, horizontal extent (fetch) of UCZ, weather, time of day/season

Applications – neighbourhood climate, more sustainable urban design, pedestrian bioclimate, building & indoor climate, design

Modified after Oke (1997)

Scales and layers relevant to urban climate



(c) Mesoscale - weather and climate at the scale of the whole city, typically tens of kilometres. Accumulated urban effects from UCZ form internal boundary layers later merging into urban 'plume'

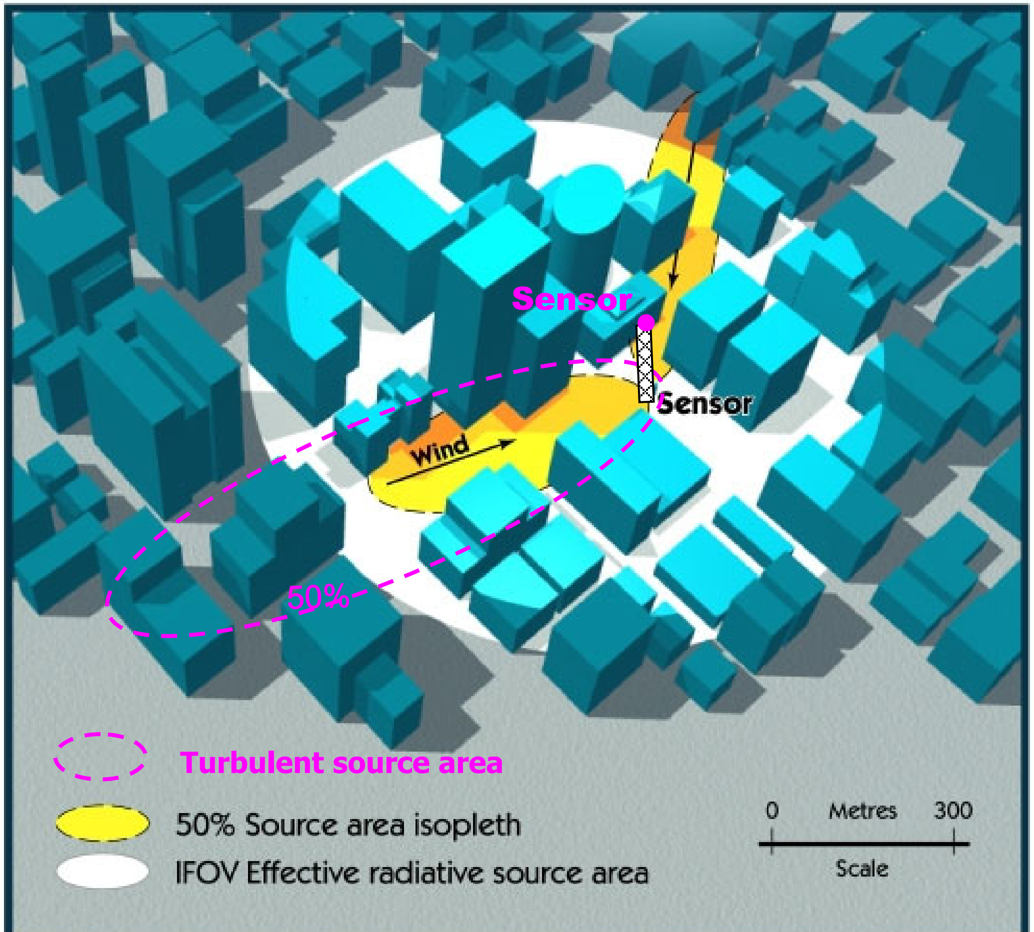
Source area – distinct UCZ of the city; scales 10-50 km. Representative UBL T_a needs airborne traverses, balloon ascents or remotely sensed profiles.

Processes – heat fluxes from top of RSL, entrainment of heat from above the UBL, air mass advection from upwind, internal radiative flux divergence

Controls – city horizontal & vertical dimensions, weather, time of day, seasonal plant growth, snow cover, soil wetness, space heating/cooling, emissions

Applications – UHI mitigation for heat waves, photochemistry of urban plume, suppression of storms, planning of urban layout

Radiative and turbulent scalar (T_a) source areas



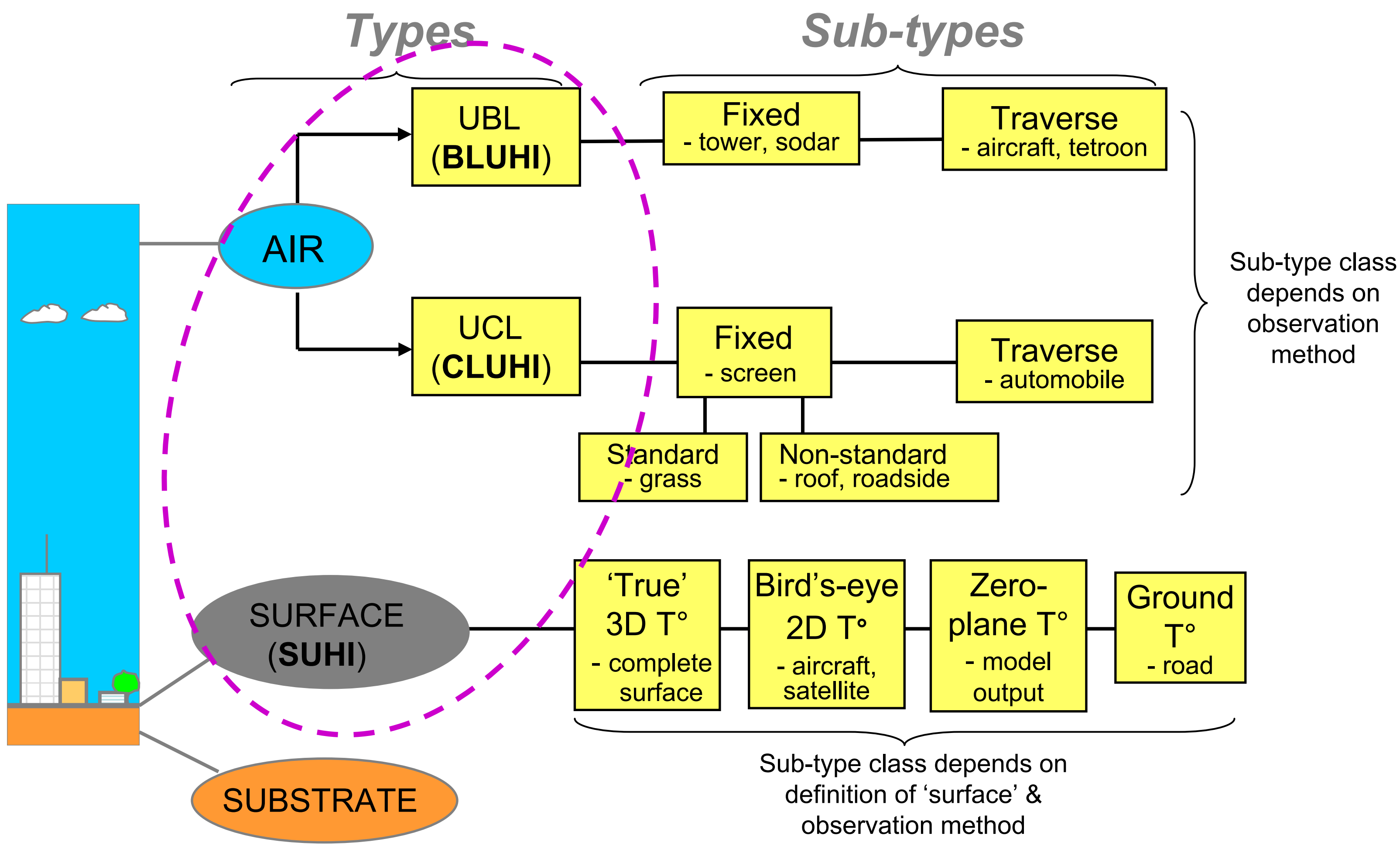
Voogt & Oke, 2003

Air temperature measured at a site are the result of the turbulent transport of heat from thermal sources lying in the upstream direction.

A sensor in the Canopy layer (UCL) are dominated by the temperature of surfaces within <0.5 km. The source area (footprint) depends on the wind direction and stability

A sensor placed above the RSL (2 to 4 times roof-level) 'sees' a much larger patch and remains dynamic

Heat island types



After Oke (1995)

Surface temperatures and ‘the’ SUHI

Temperature of surfaces depend on:

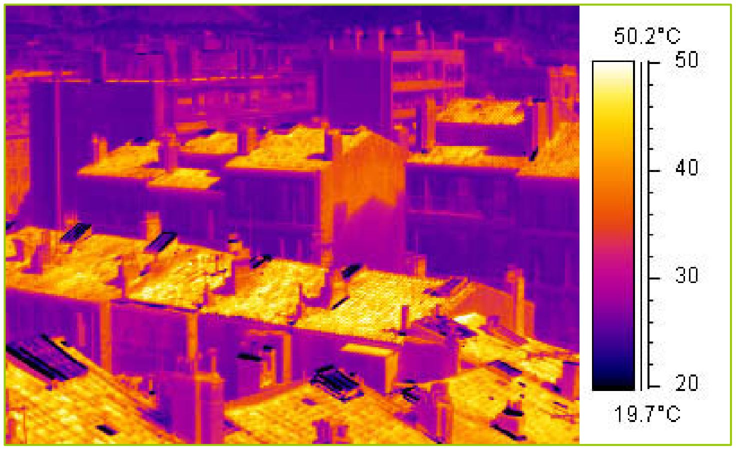


Image: Voogt, 2002

Surface energy balance, which is governed by its properties:

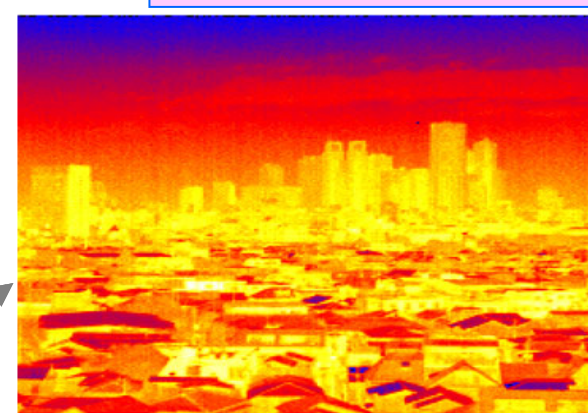
- orientation & openness to Sun, sky & wind
- radiative ability to reflect solar and infrared,
- & to emit infrared
- availability of moisture to evaporate
- ability to conduct and diffuse heat
- roughness

These facts are the basis of most mitigation:

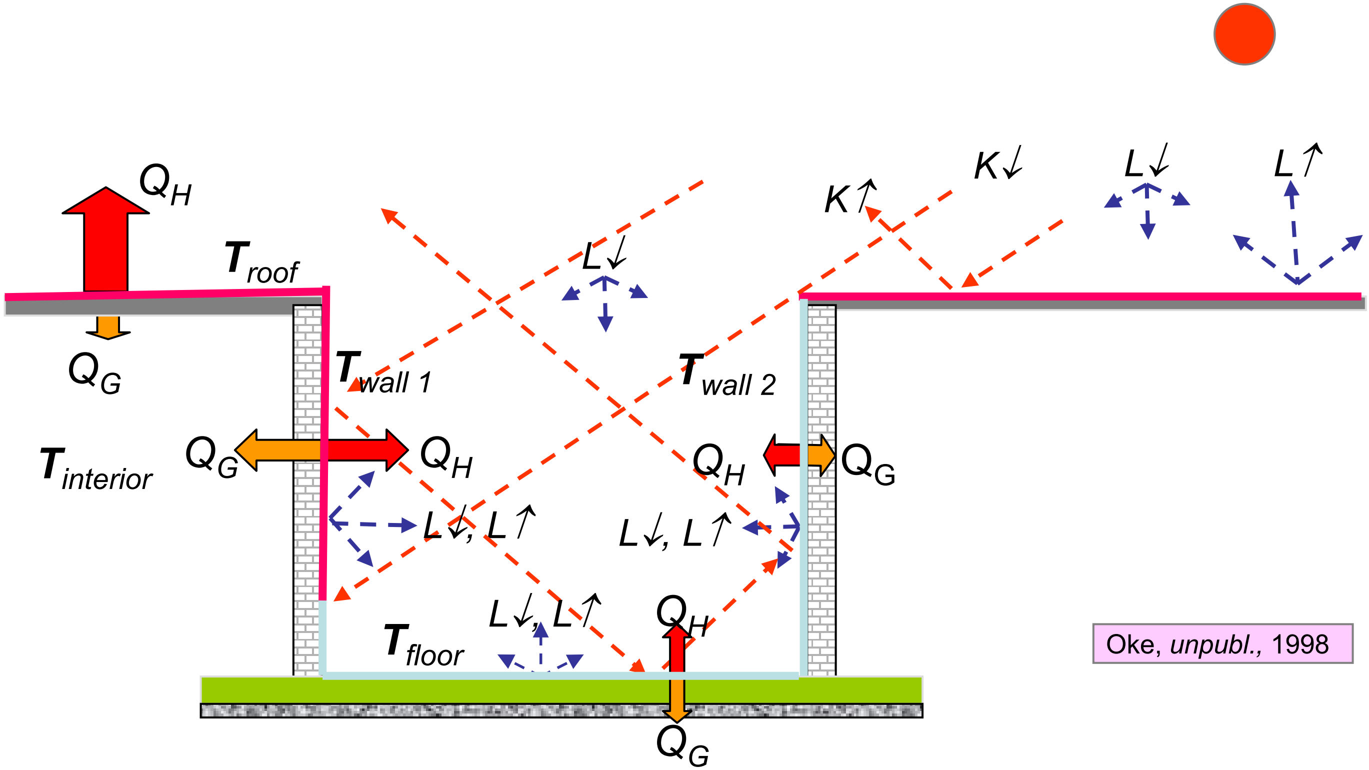
- shade & shelter (trees, awnings, narrow spaces)
- high reflection or emission of radiation (light surfaces, surface films)
- surface moisture (water, vegetation, permeable covers)
- control heat storage (massive walls, roof insulation)

Integration of all surface temperatures is ‘the’ SUHI

Image: Voogt, Roth & Kanda 2002



Heat exchanges in city core by day - SUHI



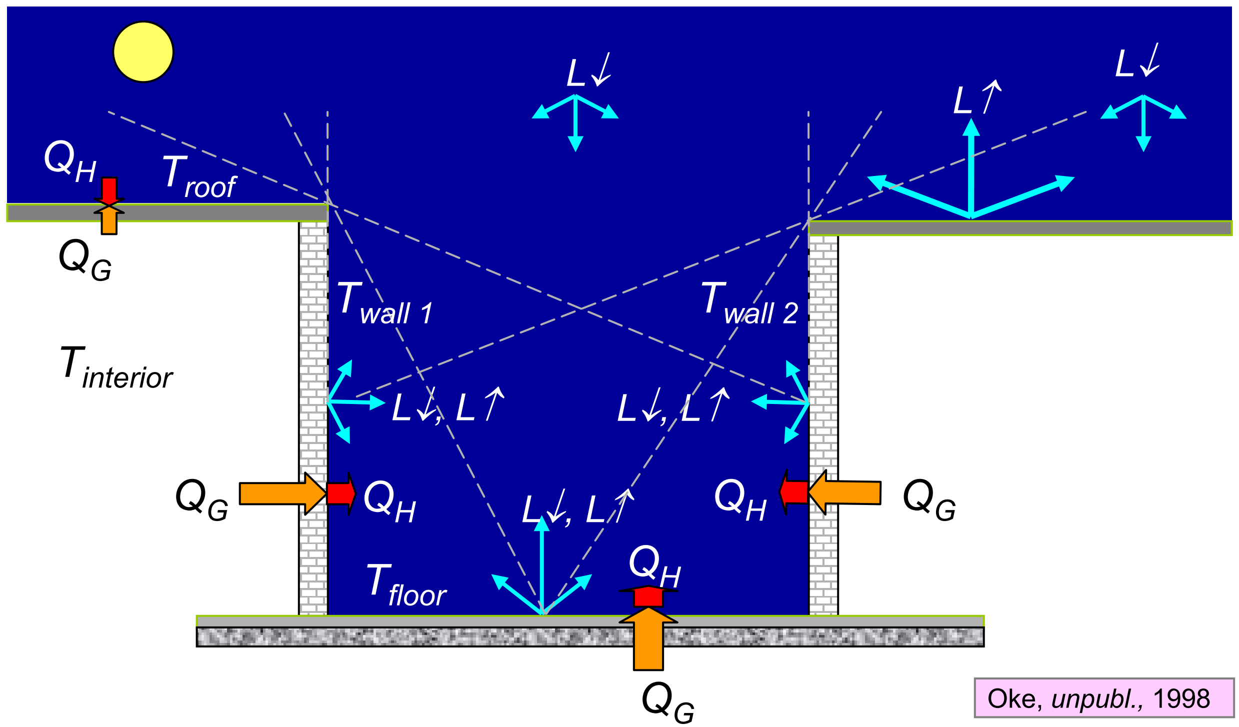
Oke, *unpubl.*, 1998

Roof surfaces - unobstructed, dark, dry, insulated → if winds weak, strong heating → very hot

Canyon surfaces - walls & floor part shaded, large area, dry, sheltered, good conduction → good heat storage → warm walls & floor unless open & sunlit

Surface *T* - $T_{roof} >> T_{walls} > T_{floor} > T_{interior}$ **SUHI** - very large positive: $T_{s\ urban} > T_{s\ rural}$

Heat exchanges in city core at night - SUHI and CLUHI



Oke, *unpubl.*, 1998

Roof s*urfaces* - large sky view, dry, insulated → if wind weak strong radiative cooling → very cold

Canyon surfaces - dry, small sky view, near calm, good conduction → weak radiative and convective drain, heat from storage and interior → warm walls & floor

Surfaces - $T_{interior} > T_{walls} > T_{floor} >> T_{roof}$ **SUHI -** large positive: $T_{s\ urban} > T_{s\ rural}$

Images of canyon daily thermal regime

Sperrstrasse, Basel, Switzerland

Voogt, unpubl., 2002

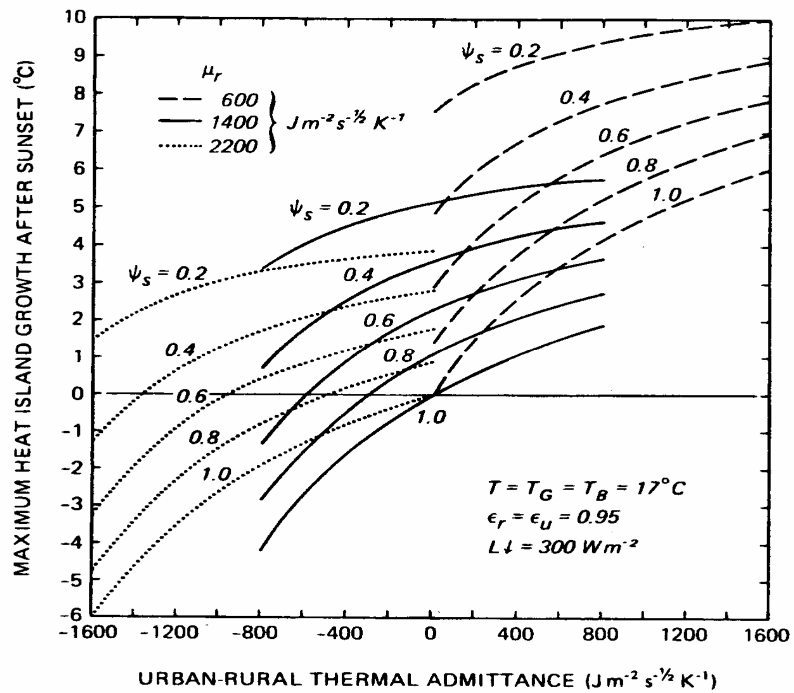
Note the radical nature of:

- absolute contrast in ***T*** of roofs and other canyon facets
- day/night reversal in relative warmth of roofs and other facets

This is significant in remote sensing because:

- generates anisotropy depending on sensor FOV
- masks true complete urban surface ***T*** when viewed from above

Relative contribution of radiation geometry and thermal properties to SUHI under ‘ideal’ nocturnal conditions



Oke *et al.*, 1991

Hence for limited cases, such as this, we know how to model SUHI if we properly include surface form and material properties. Several models do this more generally (e.g. TEB)

But this is the SUHI not the CLUHI in the canyon air. Temperature changes in the air layer above require accounting for radiative and turbulent heat flux divergence including advection

Air T change by radiative and turbulent heat flux con- /divergence

Rural air volume

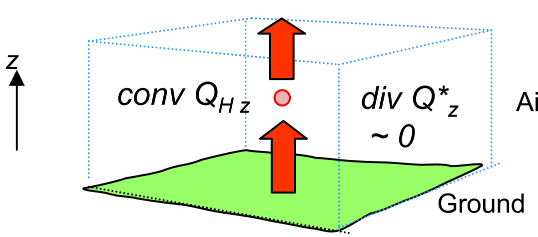
1-D flux conv/div, i.e. assuming an extensive site with little advection, $div\ Q_{E\,x,y,z}$, $div\ Q_{H\,x,y}$ and $div\ Q^*_{x,y} \sim 0$

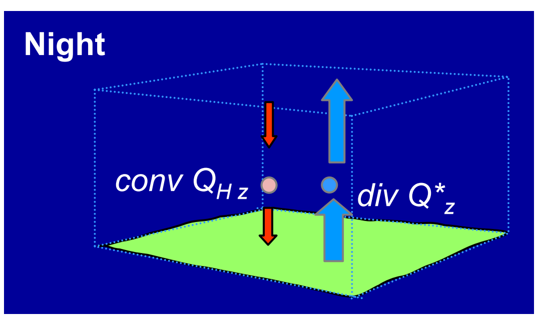
$$\boldsymbol{dQ_z = C_a\,(dTa)_z = [div\ Q^* + div\ Q_H]_z}$$

$$\boldsymbol{div\ Q^*_z = dQ^* / dz}$$

$$\boldsymbol{div\ Q_{H\,z} = dQ_H / dz}$$

Day





Urban canyon air volume

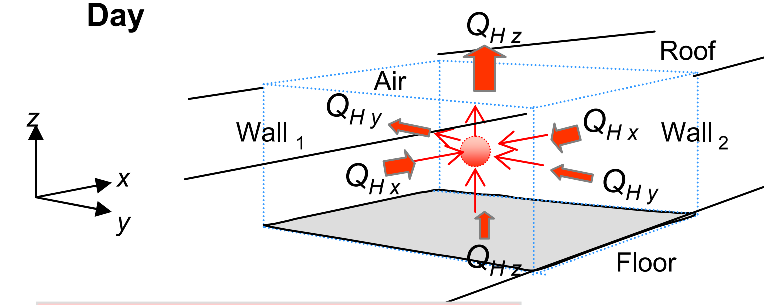
3-D flux conv/div assuming $div\ Q_E \sim 0$; $x,y,z = V$

$$\boldsymbol{dQ_V = C_a\,(d\,T_a)_V = [div\ Q^* + div\ Q_H]_V}$$

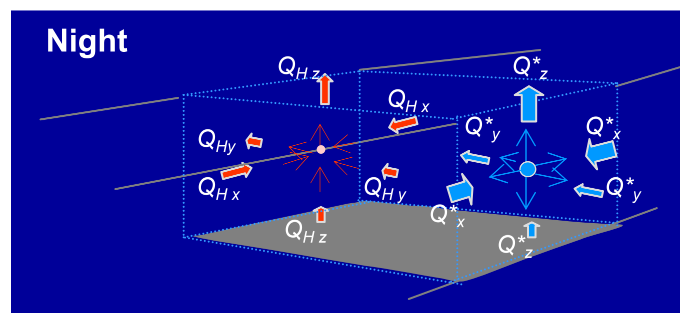
$$\boldsymbol{[div\ Q^*]_V = [\,dQ^*/dx + dQ^*/dy + dQ^*/dz\,]}$$

$$\boldsymbol{[div\ Q_H]_V = [\,dQ_H/dx + dQ_H/dy + dQ_H/dz\,]}$$

Day



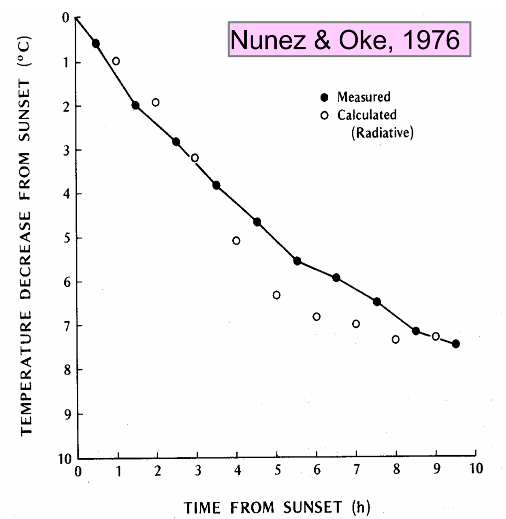
[div Q] ~ 0, so* $dQ_V \approx [div\ Q_H]_V$

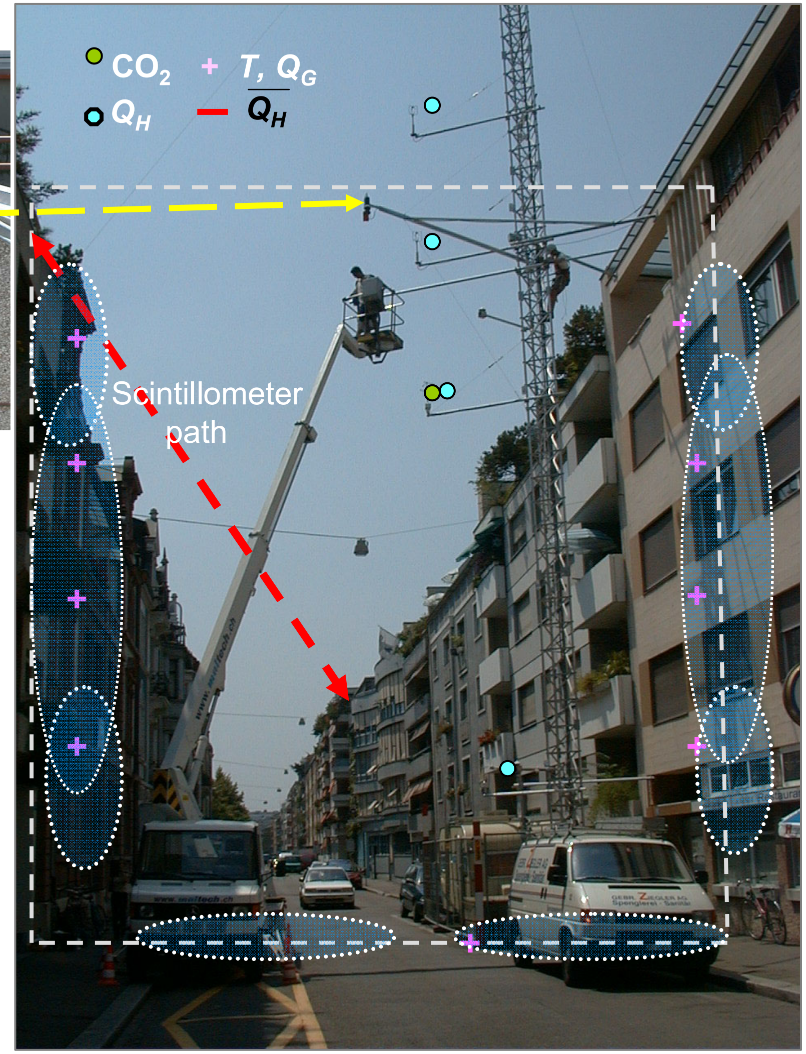


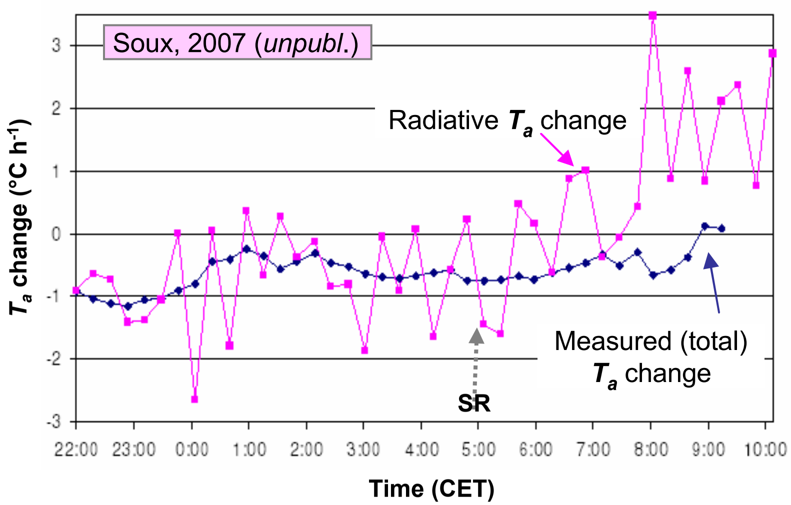
$dQ_V = [div\ Q^*]_V + [div\ Q_H]_V$

Oke, 2002a: Unpubl.

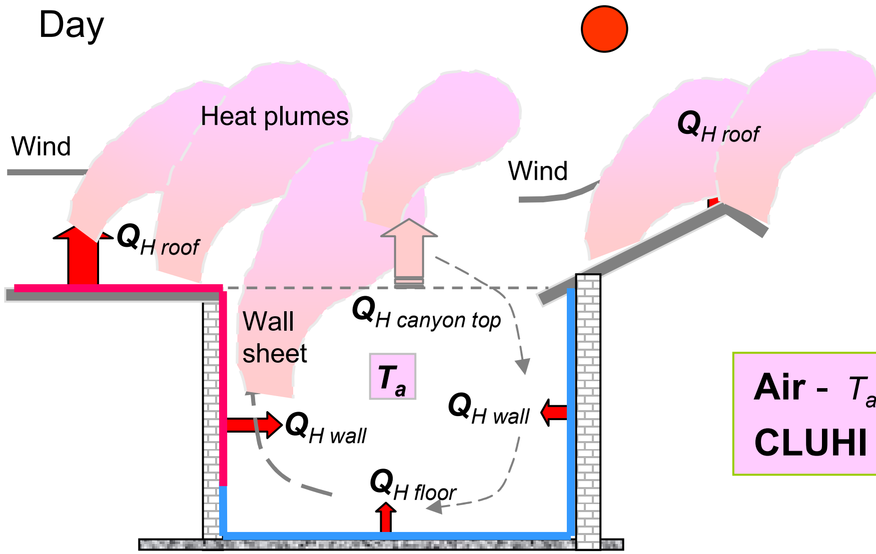
Radiative flux divergence measurement in canyons





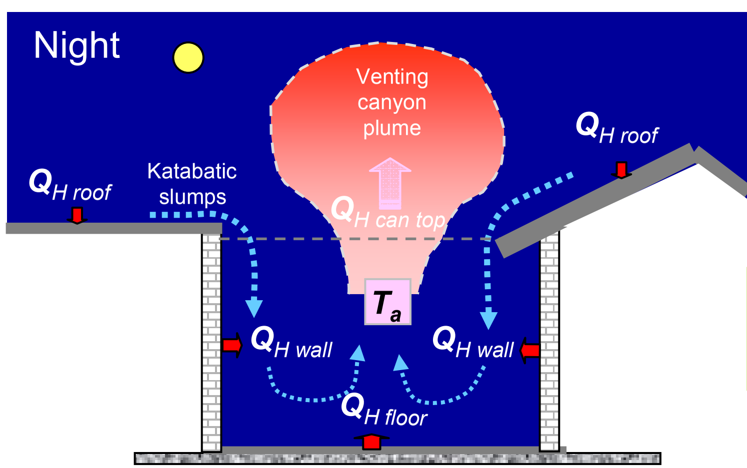


Canyon (UCL) air temperature changes



Air - $T_{a\ roof} >> T_{a\ canyon}$

CLUHI – small or even negative: $T_{a\ urban} \sim T_{a\ rural}$

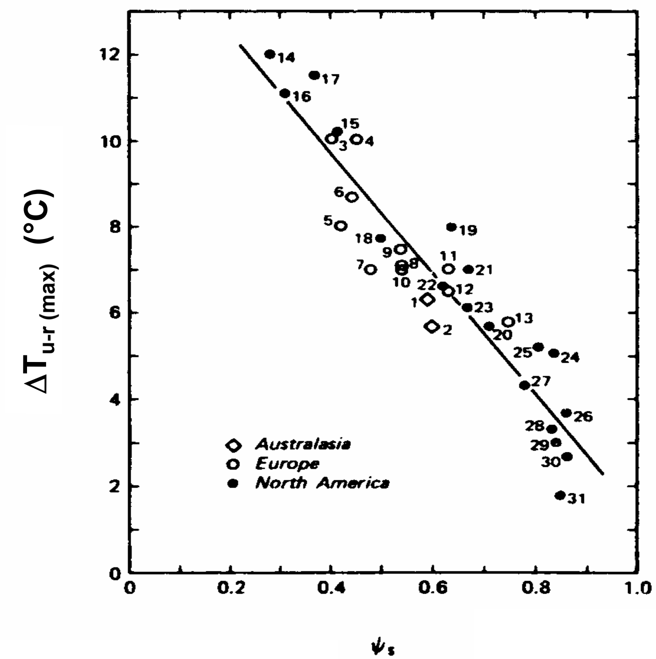


Air - $T_{a\ roof} << T_{a\ canyon}$

CLUHI – large: $T_{a\ urban} > T_{a\ rural}$

Oke, Unpul. 1998

Maximum CLUHI - on ‘ideal’ calm clear nights



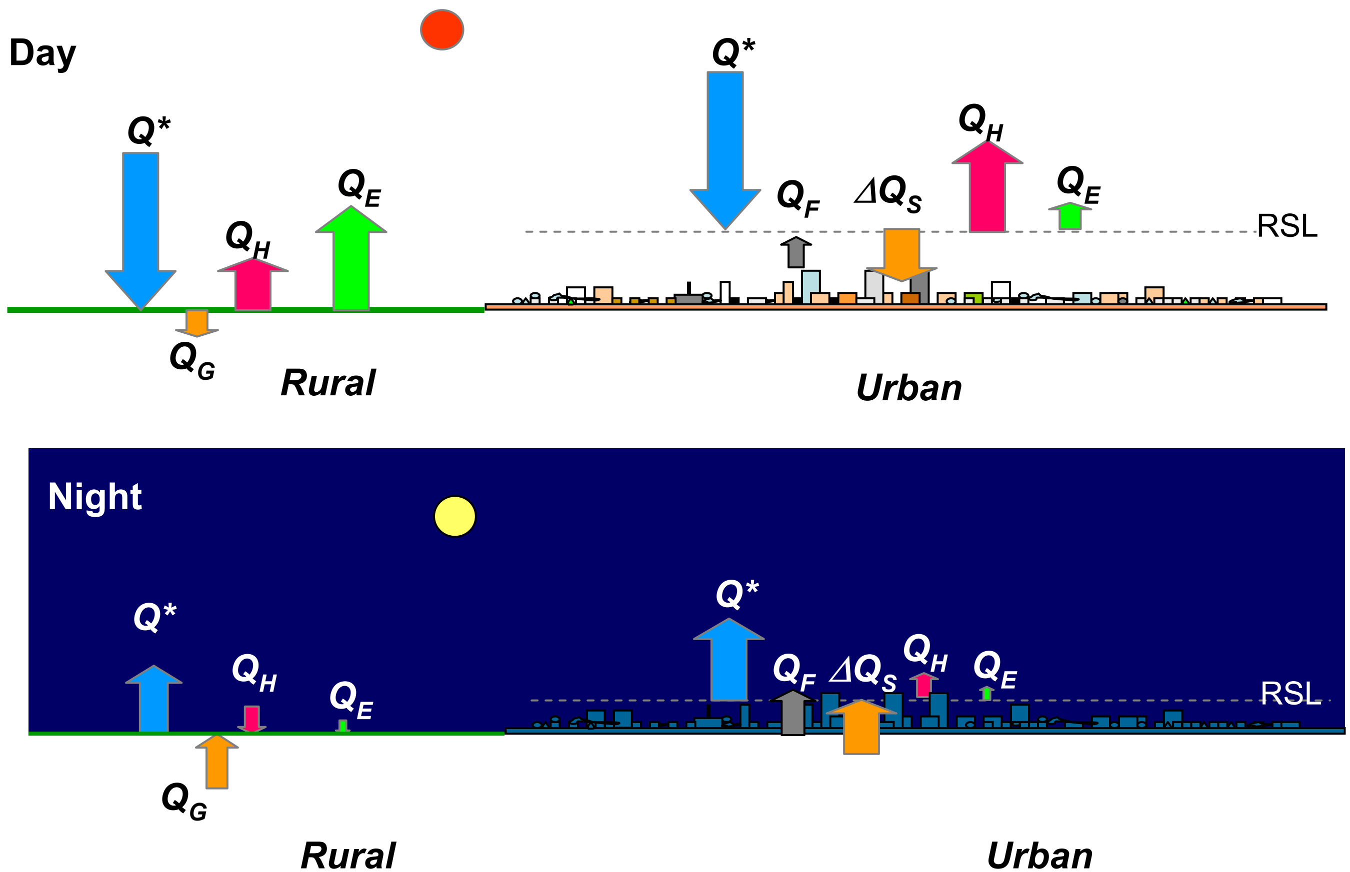
Oke, 1981

- The largest CLUHI occur on calm, clear nights after sunny days with little wind
- Tropical results cover wide range - due to rural soil moisture contrasts
- CLUHI are often approximated as differences of T_a between urban and rural sites When using such data ensure the sites are representative
- The largest recorded CLUHI are probably due to deep central street canyons (H/W or sky view of central canyons is a better measure than population)

Urban-rural energy balance differences at RSL height

The main reason for the BLUHI is urban-rural EB difference at RSL height.
Following are consistent with EB measurements in summer at mid-latitude sites

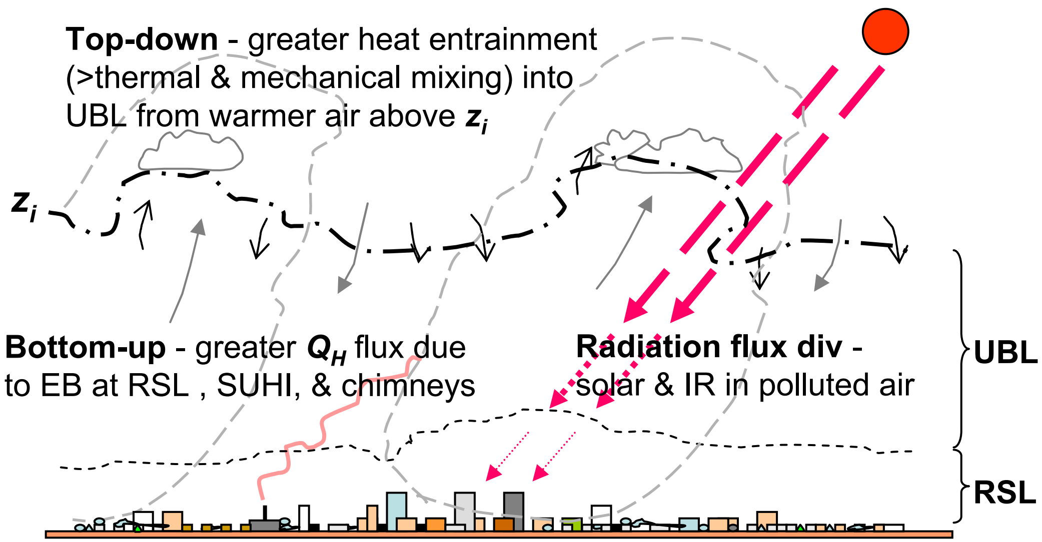
In each case: $Q^* + Q_F = Q_H + Q_E + \Delta Q_S$ (or Q_G)



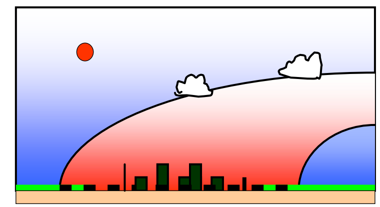
Oke, 1988: Unpubl.

UHI of the UBL - BLUHI

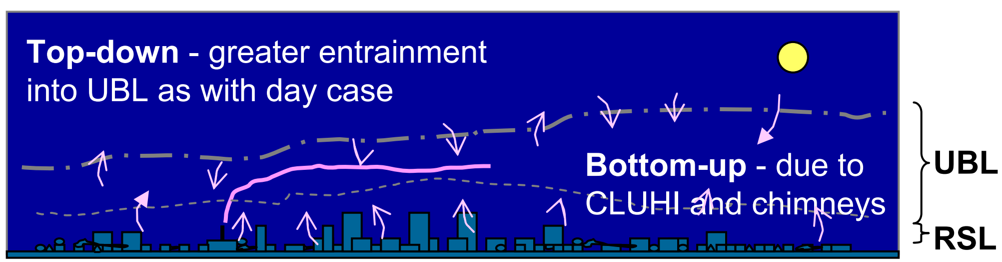
Day

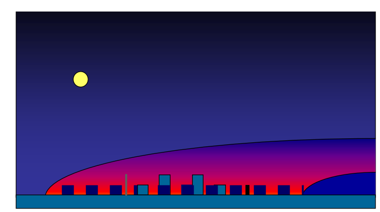


Urban heat (**BLUHI**) and pollution 'plume'



Night





Oke, Unpubl., 2002b

Scales, processes, models & observation of UHI types

UHI type	*Scale & source area*	*Processes*	*Appropriate models*	*Directly measured T*	*Remotely sensed T*
SSUHI	Micro	Sub-surface EB	Heat (water) diffusion in solid	*T* probes	-
SUHI	Micro	Surface EB	Surface EB & equilibrium surface *T*	Surface-attached *T* sensors	Corrected for atmosphere, emissivity & 3D geometry effects
CLUHI	Local	Surface EB + UCL air EB	Canopy & RSL scheme incl. canyon/roof/building radiation, conduction, convection interactions & links to sub-surface & overlying BL	Fixed (screen, mast) & mobile *T* systems in UCL & rural SL	Mini-sodar, -lidar
BLUHI	Local & Meso	RSL EB & BL EB + encroachment, flux divergence & entrainment	Boundary layer scheme including forcings by & interactions with Free Atmosphere & RSL/surface	Airborne *T* sensors (aircraft, balloons) & tall towers	Inversion techniques, sodar, lidar, profiler, RASS

Oke, Unpubl. 2008

Note: Each UHI type has a different set of scales, processes causing it, and therefore require different models to simulate, and measurement techniques to measure it

Some flaws in present methods, needs for research

Common experimental muddles and errors:

- representativeness of sites
- ‘urban-rural pairs’ paradigm, finding ‘rural’ in real world cities - *Iain Stewart*
- limitations of techniques (time & space sampling, instrument FOV, emissivity, etc) - *James Voogt*
- mixing up scales of observation, modeling
- poor experimental control (topography, wind/cloud, frontal passage, rural moisture)

Pressing research needs:

- More UBL studies - profiles and mixed layer depth and physical processes
- UCL-UBL interactions
- Physics linking SUHI, CLUHI & BLUHI
- Relative roles of radiative, conductive and turbulent processes in each UHI
- Fully verified UHI models – not just ***T*** but ***T*** & processes together
- Correctly determined temperate/tropical UHI similarities and differences
- Inventory of tropical city radiative, thermal, moisture and roughness properties
- Physical explanation of temperature/tropical UHI similarities and differences
- Standardized Guide ‘how to do UHI studies’ for user communities

Take-home messages

- There is not one heat island in a city, but several that are linked,
- They are distinguished mainly by the scales imposed by biophysical structure of a given city and the layered structure of urban atmospheres,
- Measurement of each requires arrays appropriate to that scale,
- Each is caused by its own set of scale-dependent processes,
- To model or simulate each requires a scale-dependent scheme that includes the relevant processes,
- It is incorrect to mix observed UHI features or processes or compare measured and modelled features at different scales,
- Ensure measured or modelled UHI data used for applied purposes depict the correct environmental temperature (air or surface) at the scale of the target of interest (e.g. a pedestrian, a building, a roof, airborne photochemicals)
- The Quest continues!

Source of figures in this presentation

Fortuniak, K., 2007: Presentation to 4th Polish Urban Climate Symposium, Lodz, Poland.

Nunez M. & T.R. Oke, 1976: Long-wave radiative flux divergence and nocturnal cooling of the urban atmosphere. II - Within an urban canyon, *Boundary-Layer Meteorol.*, **10**, 121-135.

Oke, T.R., 1980: Course notes for *Geog 401, Urban Meteorology*, UBC, Vancouver.

Oke, T.R., 1981: Canyon geometry and the nocturnal heat island. Comparison of scale model and field observations, *Journal Climatol.*, **1**, 237-254.

Oke, T.R., 1988; 1998; 2002a: Course notes for *Geog 401, Urban Meteorology*, UBC, Vancouver.

Oke, T.R., 1995: The heat island of the urban boundary layer: characteristics, causes and effects. In *Wind Climate in Cities*, Cermak, Davenport, Plate & D.X. Viegas, (eds.), Kluwer Acad. Publ., Dordrecht, 81-107.

Oke, T.R., 1997: Urban environments. In *Surface Climates of Canada*, Bailey, W.G., Oke, T.R. and W.R. Rouse, (eds.), McGill-Queen's University Press, 303-327.

Oke, T.R., 2002b: Presentation to Toronto Heat Island Summit, http://www.cleanairpartnership.org/agenda.htm

Oke, T.R., 2004: Initial guidance to obtain representative meteorological observations at urban sites, *IOM Report* No. **81**, WMO/TD No. 1250, World Meteor. Organiz., Geneva, 51 pp. http://www.wmo.int/web/www/IMOP/publications/IOM-81/IOM-81-UrbanMetObs.pdf

Oke, T.R., 1991: G. T. Johnson, D. G. Steyn & I. D. Watson, 1991: Simulation of nocturnal surface urban heat islands under `ideal' conditions: Part 2. Diagnosis of causation, *Bound-Layer Meteor*, **56**, 339-358.

Soux, A., 2007: unpublished doctoral research

Voogt, J.A., 2002: unpublished imagery as part of BUBBLE Project

Voogt J.A. & T.R. Oke, 2003: Thermal remote sensing of urban climates, *Remote Sens. Environ.*, **86**, 370-384.