Urban heat islands:

an overview of the research and its implications

North American Heat Island Summit

Tim Oke, UBC

Thanks to J. Voogt, UWO

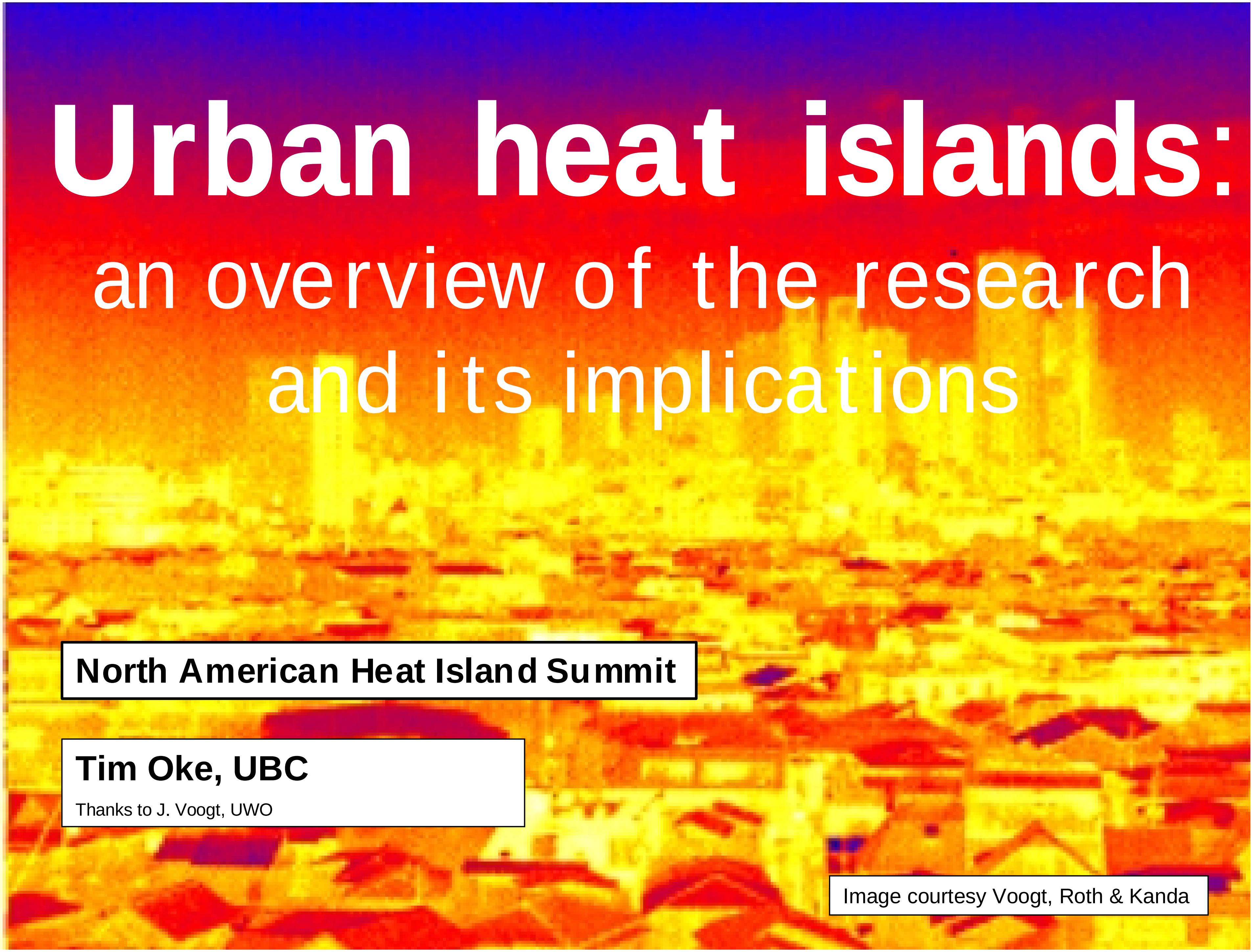
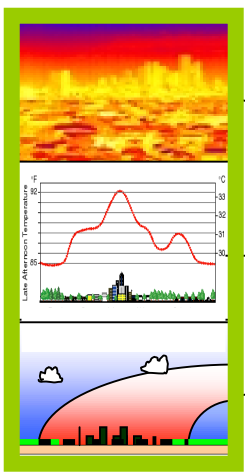


Image courtesy Voogt, Roth & Kanda

Overview

- Introduction - seems simple enough!
- Terminology (scales, surfaces, UHI types)
- Impacts of UHI - targets for control
- Nature, causes, observing, models of UHIs
  - surface (SUHI)
  - canopy layer (CLUHI)
  - boundary layer (BLUHI)
- Takeaway proposals



UHI seems simple enough

- Easily appreciated - extra warmth of cities
- Should be easy to measure - thermometry
- Simple energetic model: Heat in ± Heat out = T change
- To reduce T either reduce heat in (shade, combust less) or increase heat out (reflect, emit or convect more) or ‘hide’ heat (evaporate or put into storage)

BUT in practice UHI is more complex need to appreciate:

  - several different UHI each with own processes, spatial and temporal nature and impacts
  - wide range of scales and interactions involved
  - to design effective mitigation need not just T effects but knowledge of causative processes and predictive capacity

Thermal climatic scales relevant to this Summit

1. ***Global*** climate patterns (temperate, tropical) and changes set the base absolute temperature and its variability

2. ***Synoptic*** climate patterns and air mass dynamics underlie seasonal & multi-day thermal swings such as heat waves

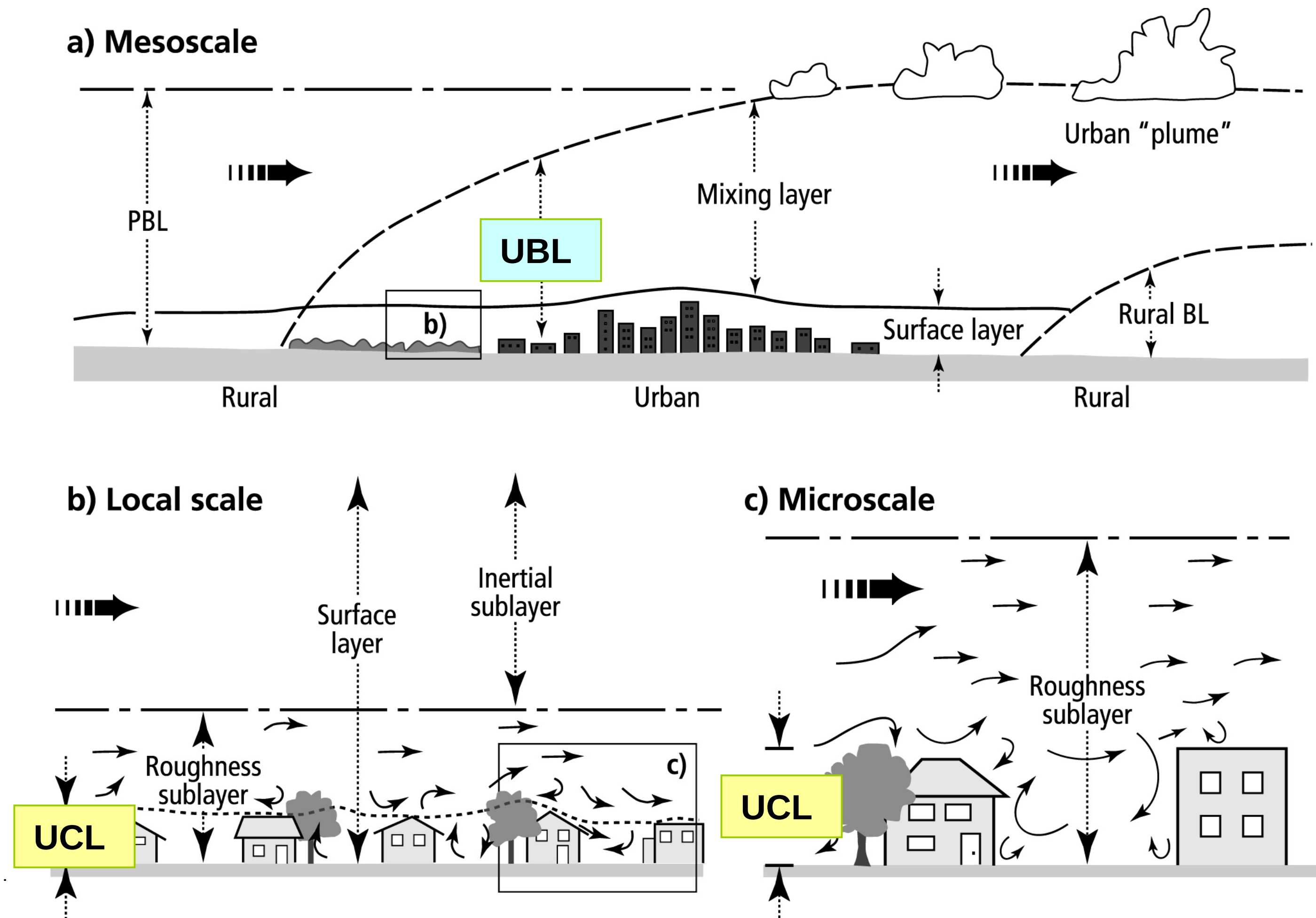
3. ***Mesoscale*** and climates such as coastal, valley and city thermal changes, breezes & cloud

4. ***Local*** climates at neighbourhood scale (parks, blocks, subdivisions)

5. ***Microscale*** climates due to the properties of individual surfaces (roofs, walls, lawns) and objects & clusters (trees, buildings, street canyons)

1 and **2** are the given base climate for a city but the ability for us to have impacts, bad or good incl. UHI mitigation, increases from **3** to **5**

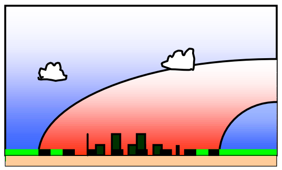
Scales and Layers Relevant to Urban Climate



Modified after Oke (1997)

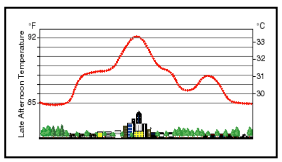
Heat island types - it isn't just 'the' UHI

Types | *Sub-types*



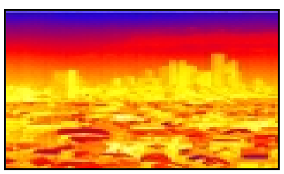
AIR

- **UBL (BLUHI)** — **Fixed** - tower, sodar — **Traverse** - aircraft, tetroon



- **UCL (CLUHI)** — Fixed - screen — **Traverse** - automobile
  - **Standard** - grass
  - **Non-standard** - roof, roadside

Depends on observation methods



SURFACE (SUHI) — **'True' 3-D T°** - complete surface — **Bird's-eye 2-D T°** - aircraft, satellite — **Zero-plane T°** - model output — **Ground T°** - road

Depends on definition of 'surface'

SUBSTRATE

After Oke (1995)

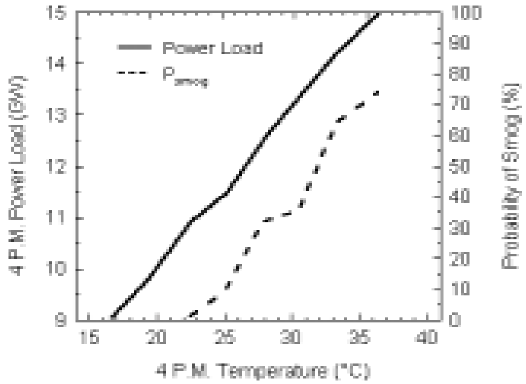
UHI impacts

(Purple are hot city impacts)

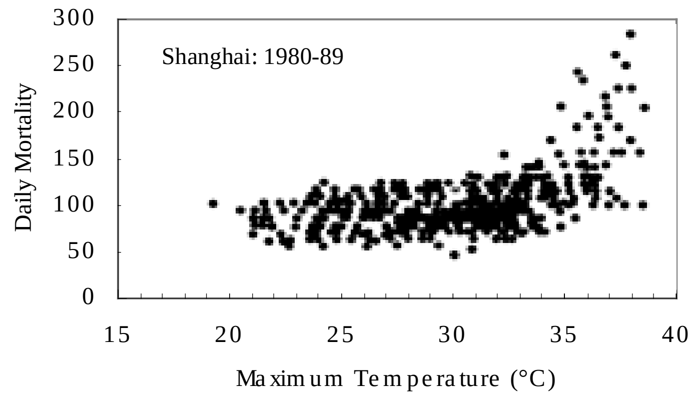
Socio-economic, health:		
Impact	***Cold Climate Region***	***Hot Climate Region***
Human comfort & mortality	Positive (winter) Negative (summer)	Negative (all seasons)
Energy use	Positive (winter) Negative (summer)	Negative
Air pollution chemistry	Negative	Negative
Air pollution dispersion	Both positive & negative	Both positive & negative
Water use	Negative	Negative
Biological activity	Positive	Probably neutral except disease
Ice and snow	Positive	Not applicable
Meteorologic:		
UHI circulation, breezes, stability, turbulence, convergence, uplift, mixed layer depth, cloud, precipitation, RH, dewfall, evaporation, fog, visibility, snow, ‘contamination’ of long-term temperature records		

Modified after Oke (1997)

Three impacts of high temperatures in cities



Los Angeles afternoon power use and air quality [Rosenfeld, 1995]



Mortality in Shanghai [Smoyer & Kalkstein, 1997]

Note the X-axis is not UHI, nor are the air temperatures taken where the emissions/photo-chemistry happens, thermostat decisions are taken, or death occurred.

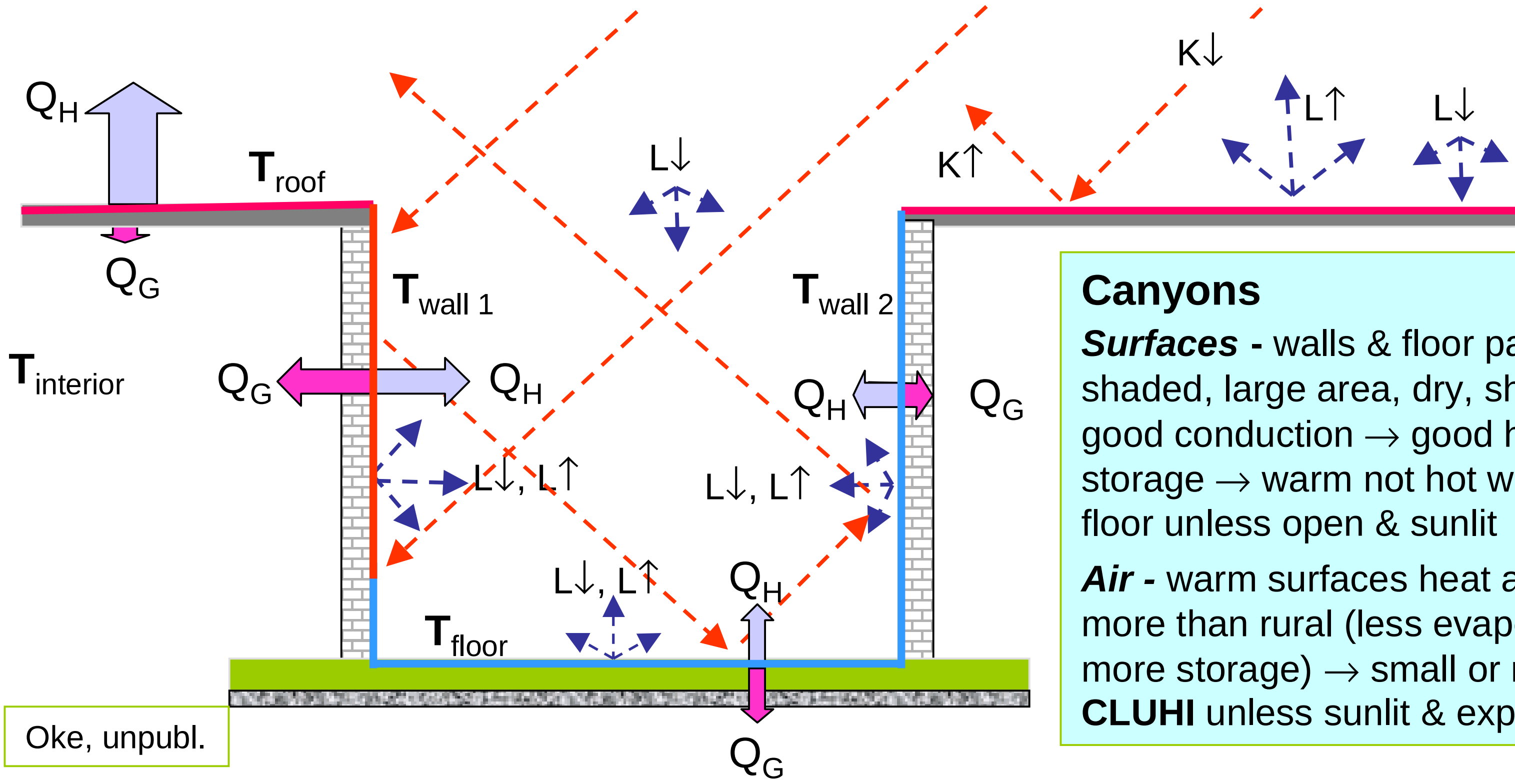
How best can we improve matters? Do we lower temperatures in the UBL ‘plume’, or UCL air temperatures everywhere, or just those of the air in buildings, or of the skin of a pedestrian or the gas tanks of cars? They are presumably all linked to the variable on the X-axis, but by very different pathways and they involve different scales & processes. To affect them positively we need to understand them.

Heat exchanges in daytime in city core - SUHI and CLUHI

Roofs

Surfaces - unobstructed, dark, dry, insulated → if winds weak, strong heating → roofs very hot

Air - contact & convective cooling → hot layer → strong convection that feeds **BLUHI**



Oke, unpubl.

Canyons

Surfaces - walls & floor part shaded, large area, dry, sheltered, good conduction → good heat storage → warm not hot walls & floor unless open & sunlit

Air - warm surfaces heat air but not more than rural (less evaporation more storage) → small or negative **CLUHI** unless sunlit & exposed

Surfaces - $T_{roof} >> T_{walls} > T_{floor} > T_{interior}$

SUHI - large positive: $\overline{T}_{s\ urban} > \overline{T}_{s\ rural}$

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

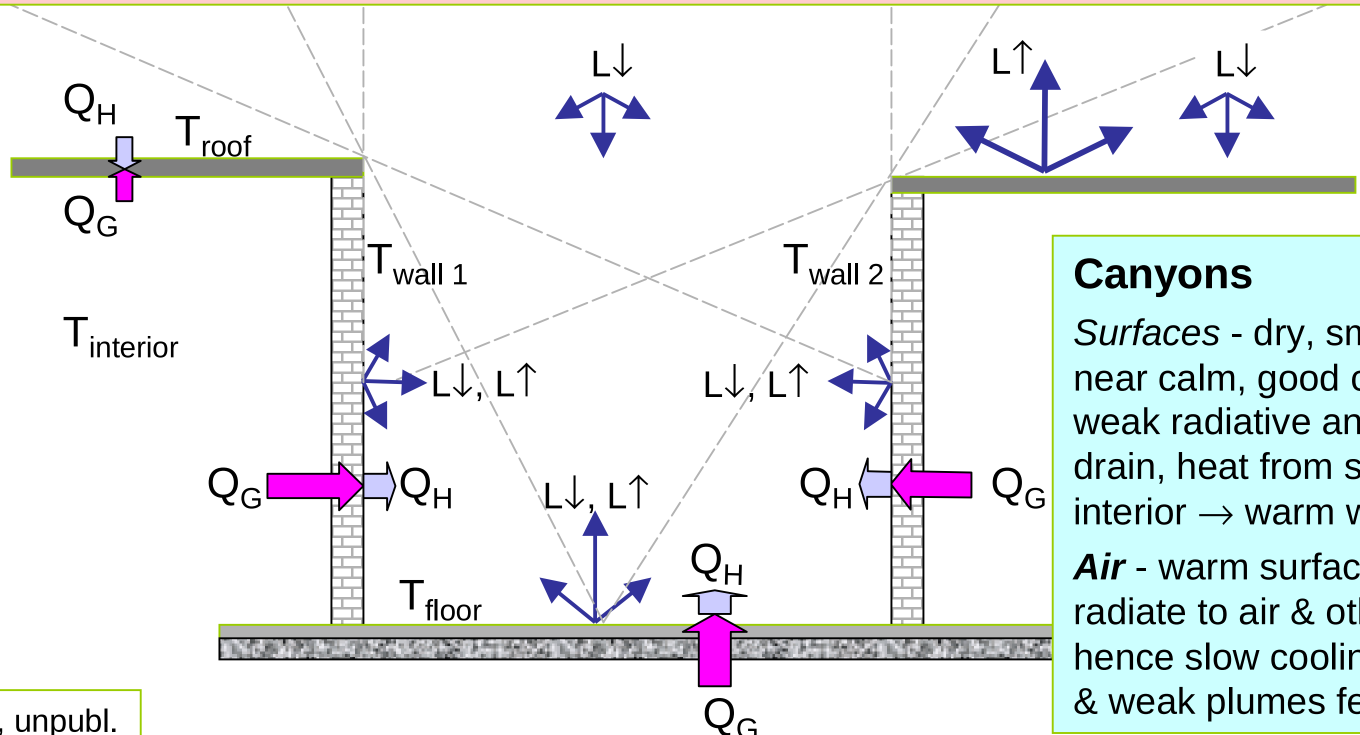
CLUHI - small: $\overline{T}_{a\ urban} \sim \overline{T}_{a\ rural}$

Heat exchanges at night in city core - SUHI and CLUHI

Roofs

Surfaces - large sky view, dry, insulated → if winds weak strong radiative cooling → very cold

Air - contact & convective cooling → cold layer, occasional katabatic slumps into canyons



Canyons

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

Air - warm surfaces convect & radiate to air & other surfaces hence slow cooling → **CLUHI,** & weak plumes feed **BLUHI**

Oke, unpubl.

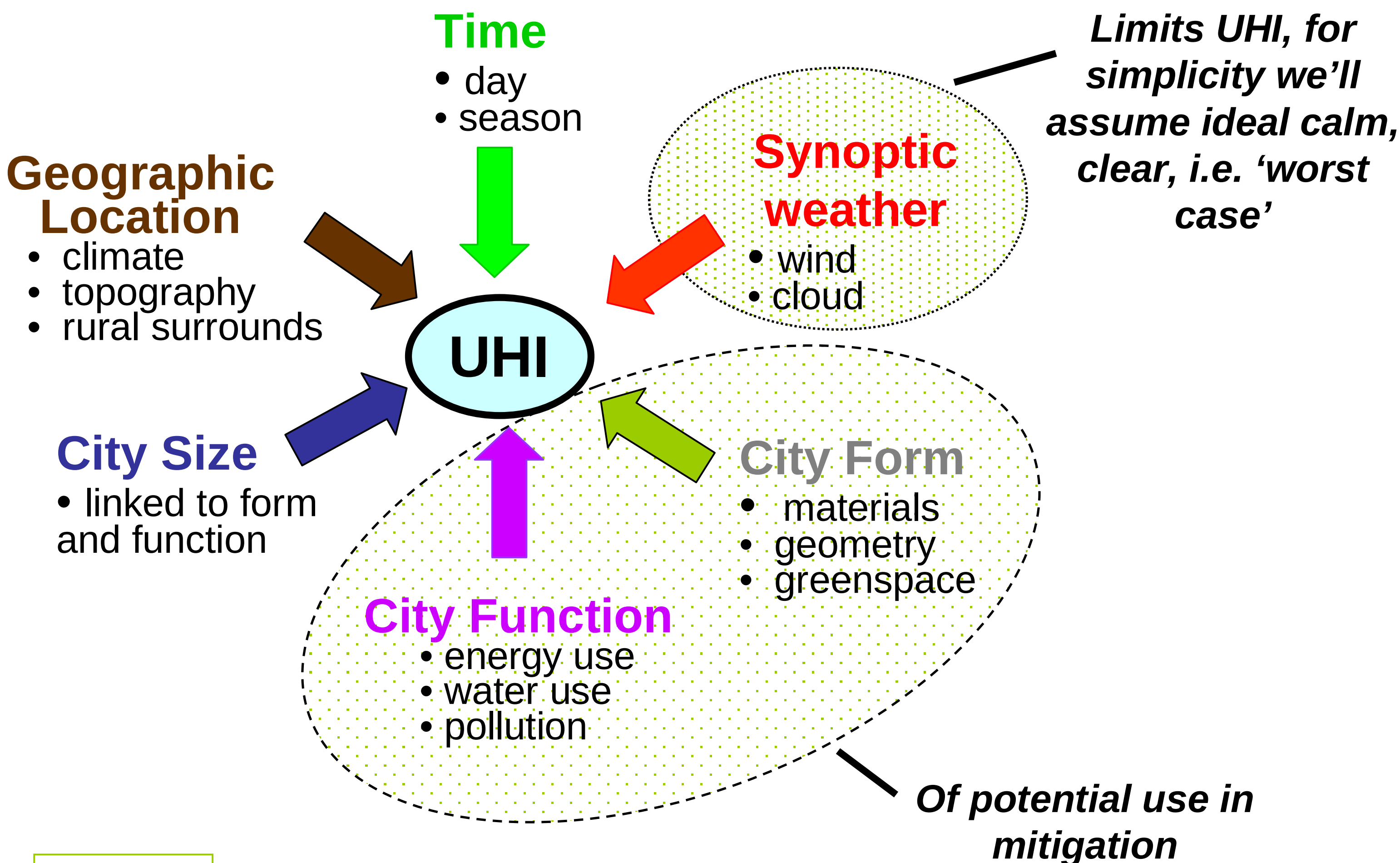
Surfaces - $T_{interior} > T_{walls} > T_{floor} >> T_{roof}$

SUHI - positive: $\overline{T}_{s\ urban} > \overline{T}_{s\ rural}$

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

CLUHI - large, positive: $\overline{T}_{a\ urban} > \overline{T}_{a\ rural}$

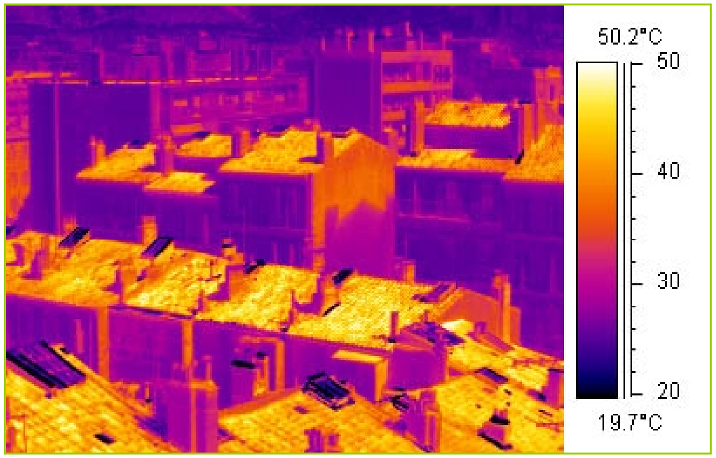
Controls on the UHI



Oke, unpubl.

Surface temperatures and ‘the’ SUHI

Temperature of every surface depends on: its surface energy balance, which is governed by its properties:

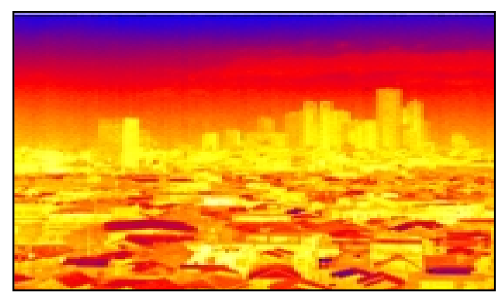


- orientation and openness to Sun, sky and wind
- radiative ability to reflect solar and infrared, and to emit infrared
- availability of surface moisture to evaporate
- ability to conduct and diffuse heat
- roughness

These facts are the basis of most mitigation methods, i.e. the provision of:

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

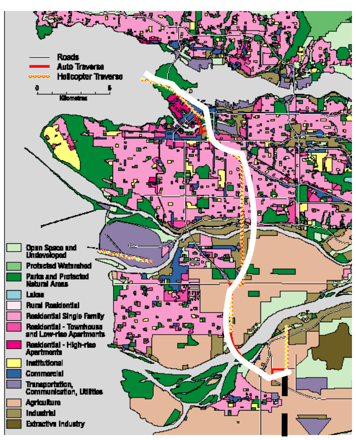
The integration of all these micro surface temperatures constitutes ‘the’ SUHI →



Oke unpubl.

Remote measurement of SUHI

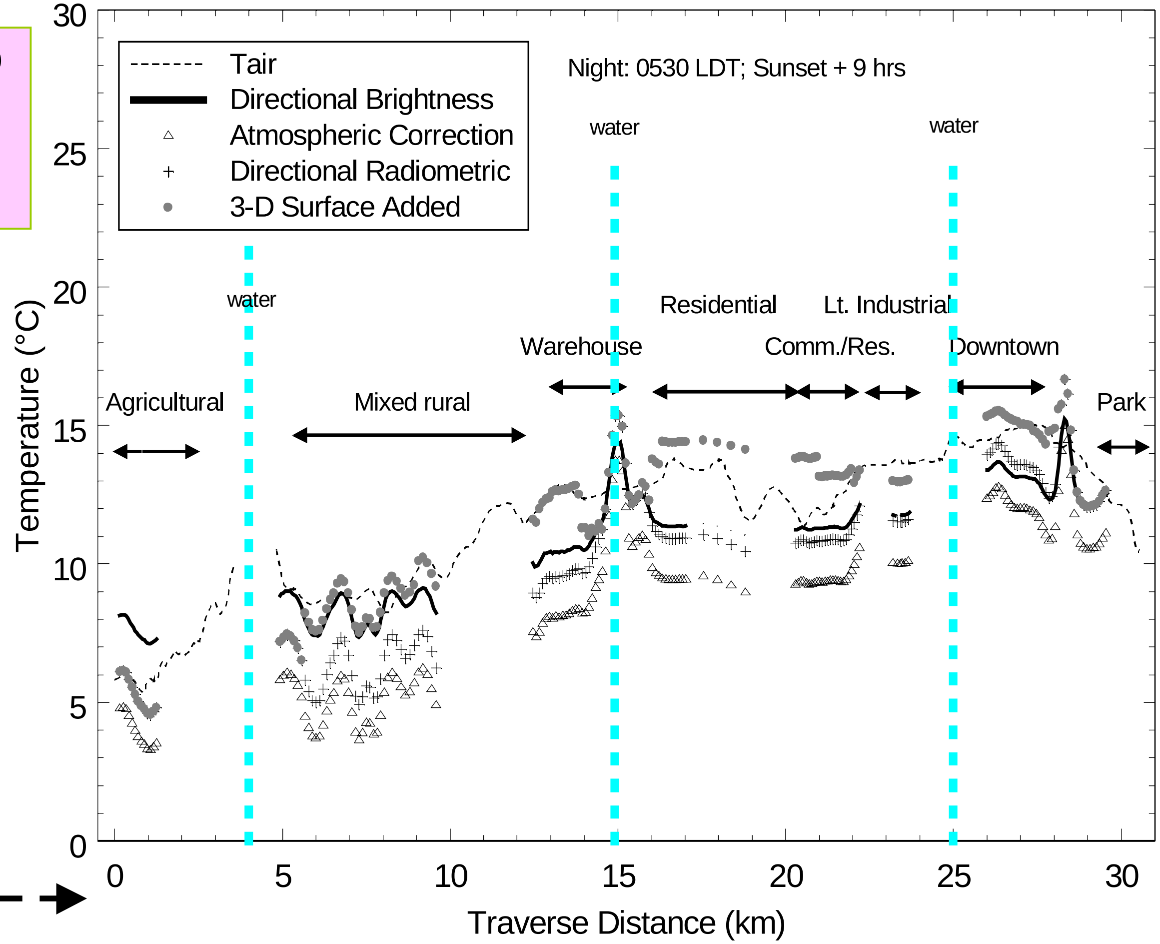
Remote sensing of absolute T_s & SUHI needs corrections - be aware of errors for modelling, fluxes & climate interpretation - more research



SUHI

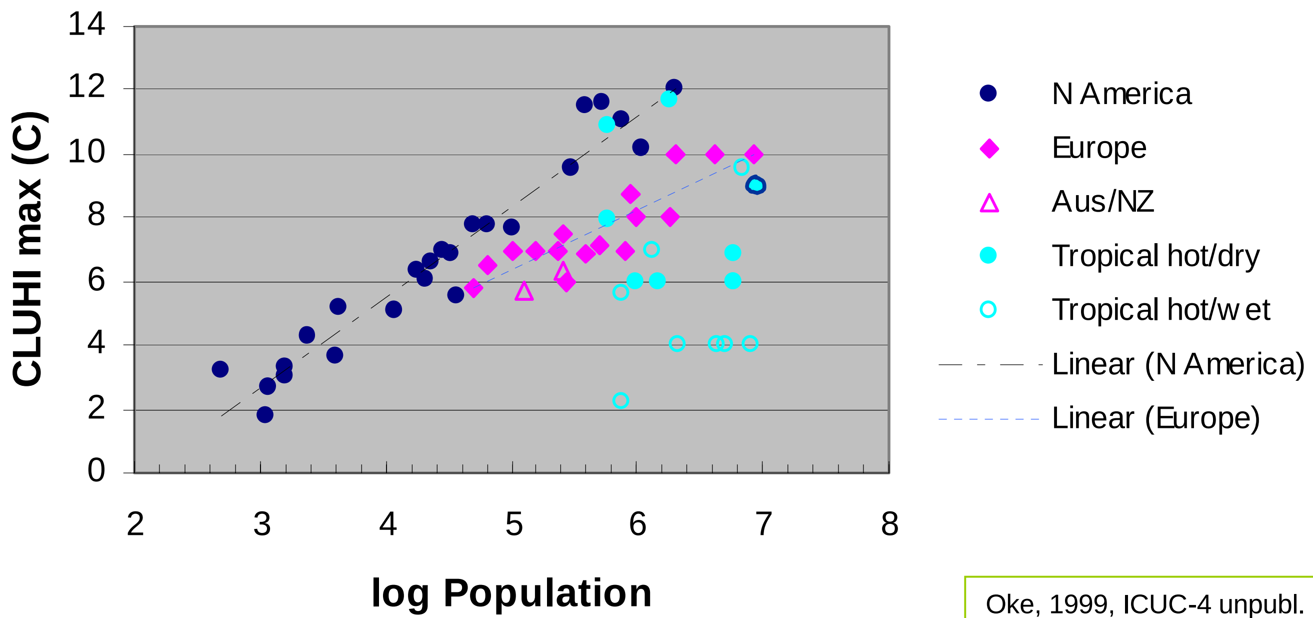
10
6
8
9
10

Vancouver, BC



Voogt & Oke, 2002

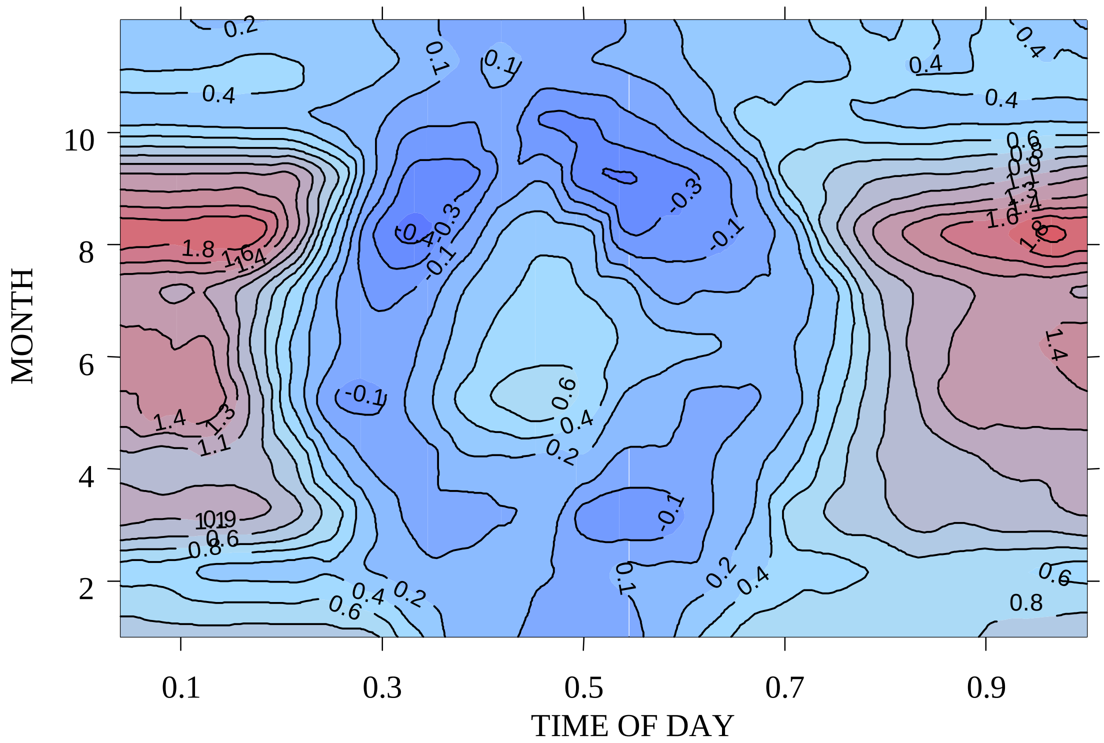
Maximum CLUHI - on 'ideal' calm clear nights



Oke, 1999, ICUC-4 unpubl.

- The largest CLUHI occur on calm, clear nights after sunny days with little wind
- The largest recorded CLUHI show North America top of the table - uh, oh ! Probably due to deep central street canyons (H/W or sky view of central canyons is a better measure than population).
- 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 - they can be bizarre!

Typical hourly CLUHI [°C] of Lodz, Poland

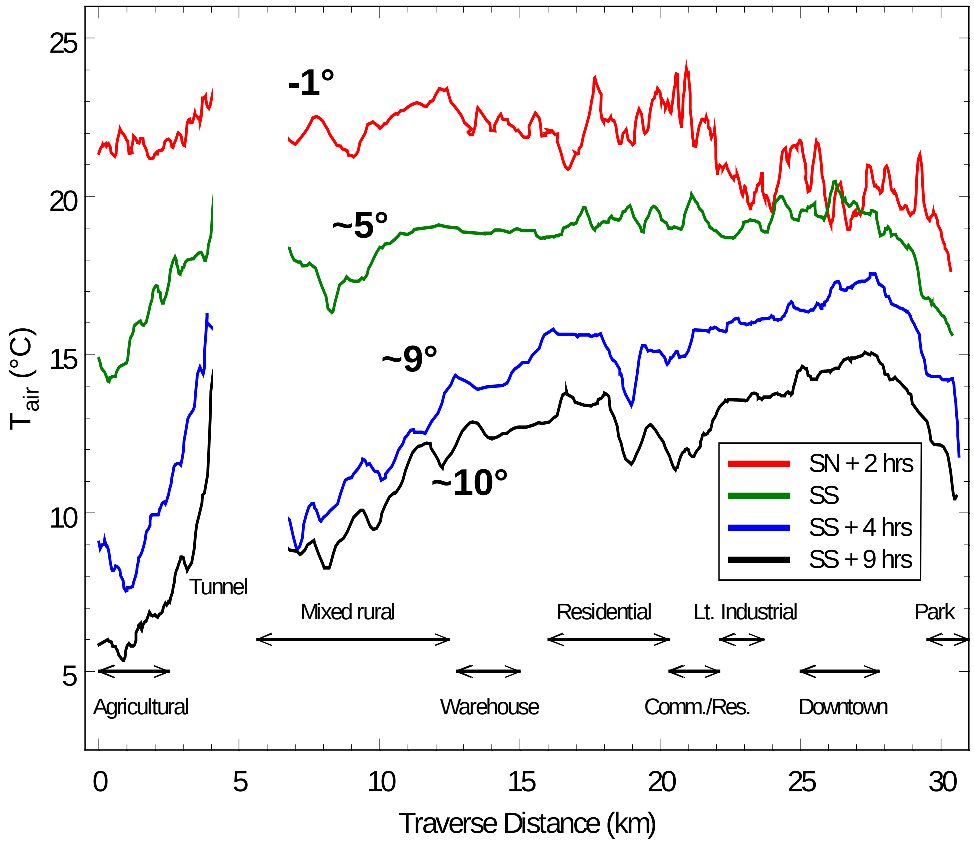


The urban-rural sites for this set of data are well sited and clearly show:

- seasonal pattern with daylength and the control exerted by synoptic weather (wind, cloud & high rural wetness reduce CLUHI)
- daily pattern with daytime minimum (negative) and nocturnal maximum

Data supplied by Klysik and Fortuniak

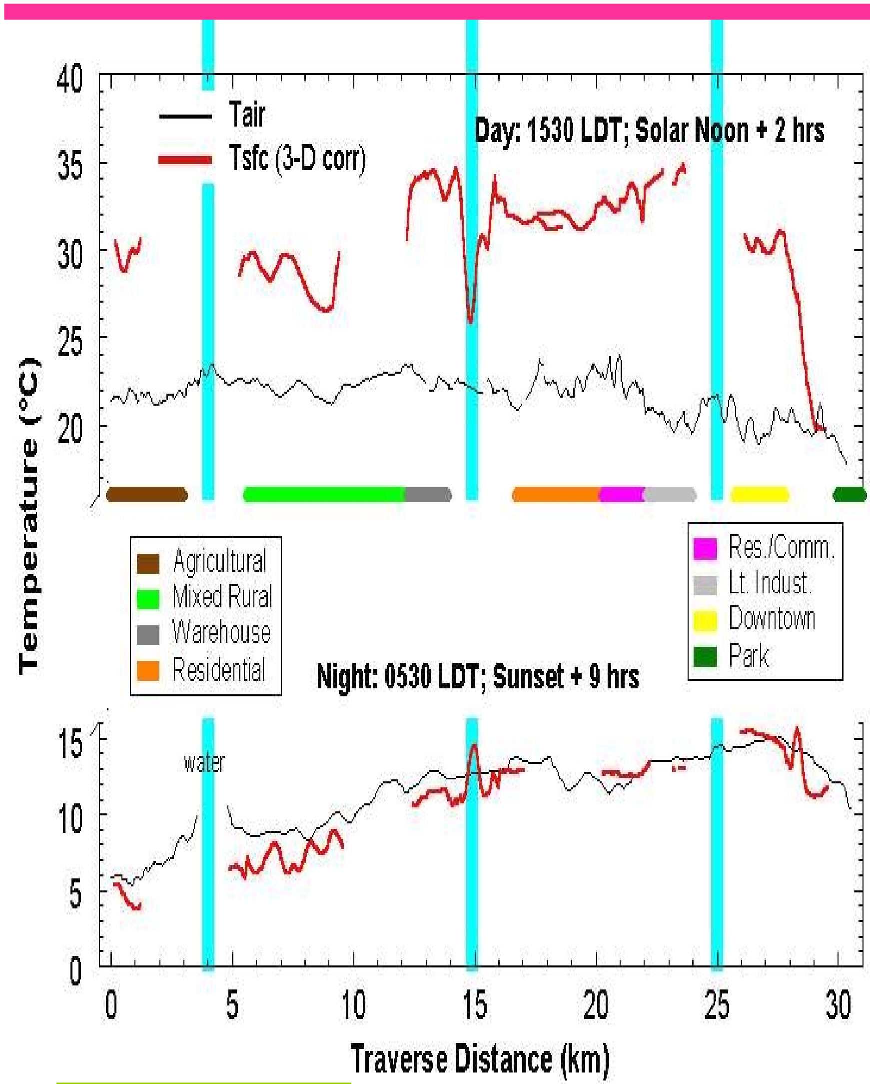
Cross-sections through Vancouver's CLUHI at 4 times on a fine August day (same day as SUHI results)



Voogt & Oke, unpubl.

- Afternoon CLUHI is negative
- By sunset it is growing fast
- Maximum at end of night
- Rural has cooled 16° but city core by only 6°.
- CLUHI is due to thermal inertia. Difficulty in canopy warming up and cooling down.
- Differences from such a classic pattern may be due to:
  - topography (coasts, valleys)
  - unusually dry or wet rural soils
  - forest

Synchronous T_s (SUHI) and T_a (CLUHI)



Voogt & Oke, unpubl.

Simultaneous data for surface T (fully corrected) and canopy T:

Nighttime

- **T_s ~ T_a** - almost neutral stability in city, inversion in country
- **SUHI ≅ CLUHI** (~10° each)

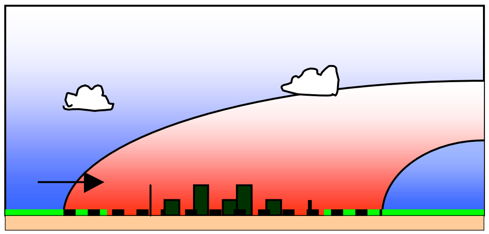
Daytime

- **T_s » T_a** - indicates major instability and probably larger sensible heat flux to feed BLUHI
- **SUHI » CLUHI** (5° vs. -1°)

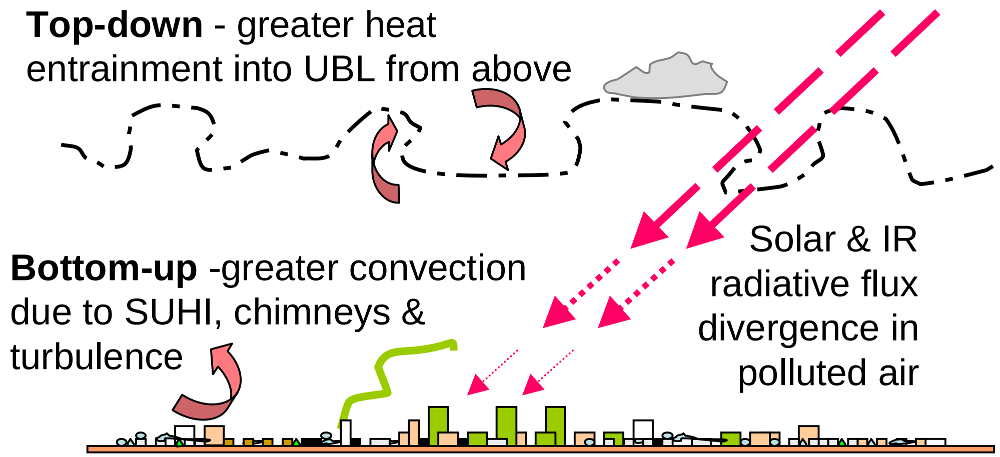
The small daytime CLUHI is clue that heat is going into storage, this will produce next night's large UHI - hence daytime mitigation is key.

Heat island of Urban Boundary Layer (BLUHI)

Urban heat (BLUHI)
and pollution 'plume'



Measured from towers, balloons, aircraft



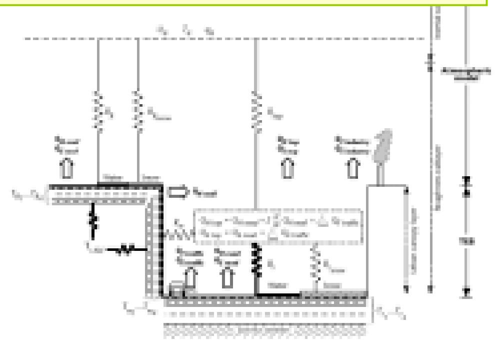
- Mean UBL anomaly ~1.5°C, extends up to 1 km and up to 40 km downstream
- Urban 'plume' is warm/dry by day and warm/moist at night
- Greater instability may give extra cloud, precipitation and fumigation
- Extra warmth accelerates photochemistry leading to O_3
- Validated mesoscale climate and pollution models valuable to test scenarios

Mitigation of BLUHI focus on reducing SUHI and to lesser extent CLUHI - again daytime mitigation is the key to both daytime and nocturnal anomaly.

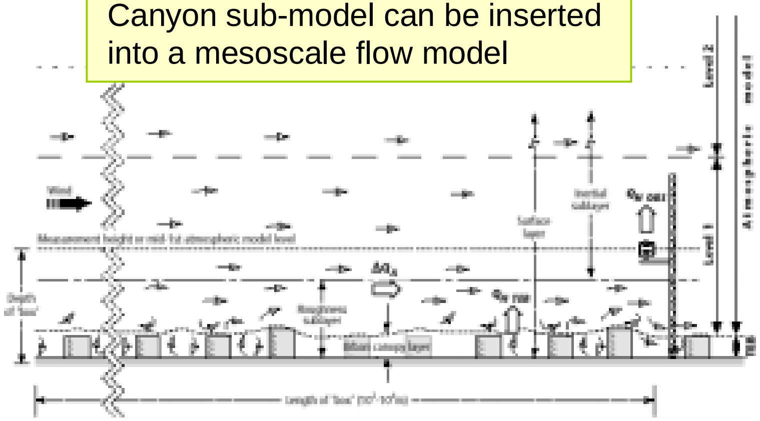
Validation of TEB mesoscale model

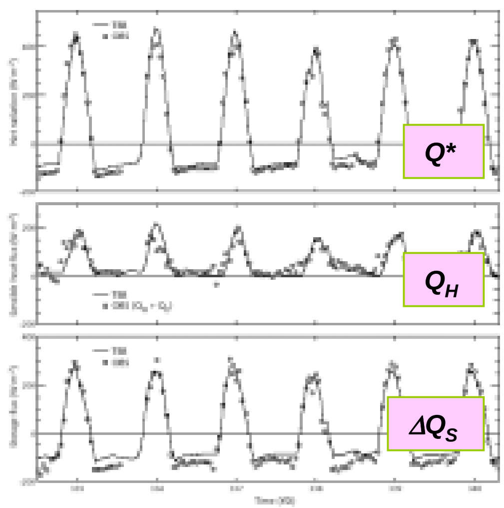
Masson *et al*., 2002

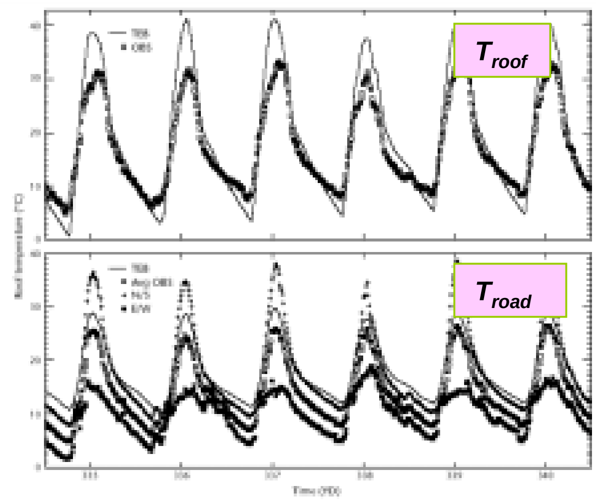
TEB canyon-scale model for fluxes and T of roof, walls and floor,



Canyon sub-model can be inserted into a mesoscale flow model



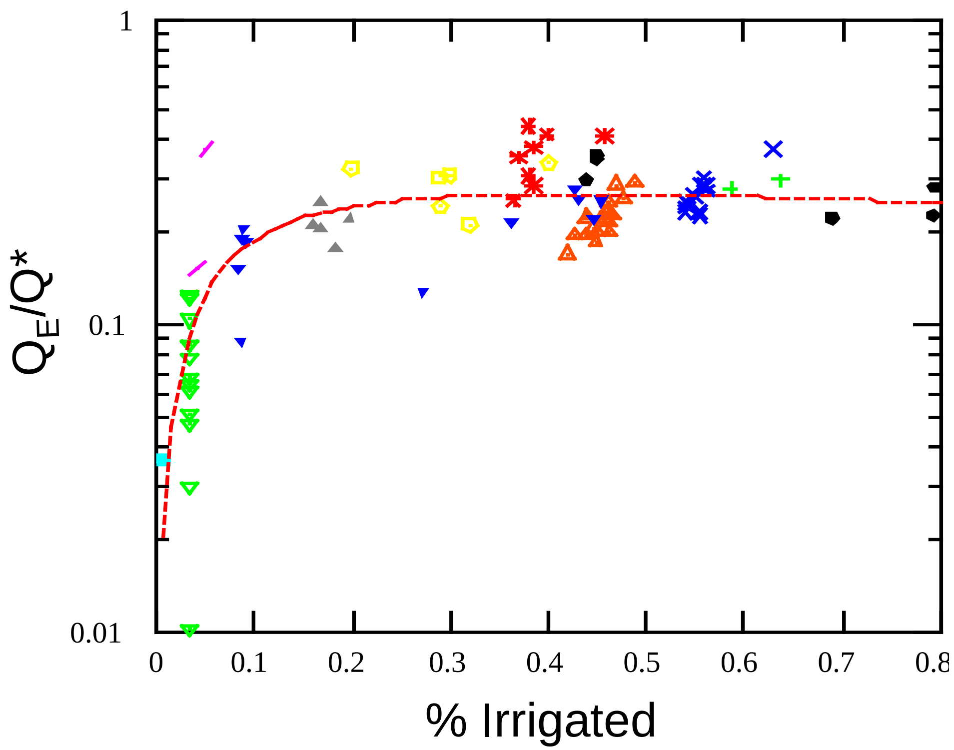




Surface fluxes weighted to give canyon-scale values, Compared with measured fluxes from Mexico City

Also compared with measured roof and road temperatures from Mexico City

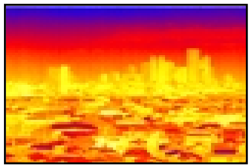
Evaporative fraction vs % irrigated



Grimmond & Oke, 2002

Measurements of areal evaporation from cities are now available and show plan area of vegetation, and especially of irrigated greenspace, may have relatively little additional impact beyond coverage ~30%.

Implications of UHI research for field



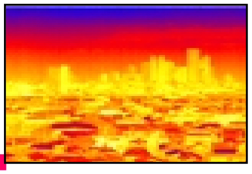
Weakness

Several UHI with differences in magnitude, daily timing, measurement needs, environment affected and implications for impacts. Glossing over these differences leads to misunderstanding, slows progress, is a waste of time and funds, and hampers mitigation efforts.

Proposals

- adopt precise UHI-type names and use them
- establish measurement protocols for each UHI
- correct remotely-sensed imagery (research algorithms, emissivity of areas, surface structure and materials not land-use)
- insist models be validated
- validate using UHI data matched to model output
- validate using heat fluxes as well as temperatures
- users must ensure measured data or model output is valid for purpose (errors, sites, UHI-type)

Implications of UHI research for field



Summary assessment on research

- more work on UHI energetics, remote sensing and modelling is clearly needed
- until the above are forwarded assessment of effectiveness of mitigation measures, especially at larger scales remains largely speculation and trial-and-error. There is much wasteful replication of effects studies (each depends on local boundary conditions)
- potential negative outcomes of mitigation cannot be accurately weighed (humidification vs cooling by water and vegetation, reduction of mixing height and UHI circulation, pedestrian glare, etc.)
- in the meantime cool away! Targeted cooling of individual features (shading of houses, bus stops, parking lots etc.), light roofs, porous pavement, etc is undeniably good as is general softening of hydrologic response and ecologically healthy greening.