
How to do Urban Climatology: a Personal View of the Legacy of Professor Tim Oke



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Preface

- This material was prepared for the session recognising the achievements of Dr. T.R. Oke, on his retirement, at the Sixth International Conference on Urban Climate (June 12-16, 2006, Göteborg, Sweden)
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Outline

- Definitions
 - Preface: some preliminary remarks
 - The Major Themes: a brief review of the framework and major findings of a subset of modern urban climatology from the perspective of Oke's work
 - The Oke Contribution: a personal assessment the Oke contribution to the vigour, rigour, visibility, scope and content of urban climatology
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Definitions

- Following Oke (2006), I will use the term urban climate to include “the study of meteorological processes, atmospheric phenomena, and the longer term amalgam expression of these as climates in areas that have undergone urban development.” Likewise with derived words such as “urban climatology” or “urban climatologist”.
 - In the following, I will include within the Oke *opus* any work on which his name appears in the author list and will make no attempt to differentiate Oke’s work from that of his co-authors.
 - I am confining consideration to the published, peer-reviewed literature in urban climate and will *not* include reports, non-refereed articles, proceedings etc.
 - Finally, I shall in places use the following abbreviations for energy budget components
 - Q^* flux density of net radiation
 - Q_H turbulent flux density of sensible heat
 - Q_E turbulent flux density of latent heat
 - ΔQ_S storage heat flux density (in local scale budget)
 - Q_G substrate heat flux density (in budget for a simple surface)
-

Preface [1]

- Timothy R. Oke: PhD (McMaster University), Geography, 1967
 - Dissertation: *Super-surface Minimum Temperatures at Night*
 - First publications in urban climatology (as Assistant Professor, McGill University):
 - 1968. Some results of a pilot study of the urban climate in Montreal. *McGill Climatological Bulletin* 3, 36-41
 - 1969. Towards a more rational understanding of the urban heat island. *McGill Climatological Bulletin* 5, 1-21
-

Preface [2]

- Themes in Oke's first publications:

- City effects in changing radiation and energy budgets
 - Vertical extent of the city influence on the atmosphere
 - 3D structure of the urban heat island and its dependence on meteorological conditions
 - Meticulous attention to experimental design, observation and sampling error and to theory-measurement coupling
 - Emphasis on the study of process with the objective of establishing a sounder physical basis for urban climates
 - Urban-rural contrasts in surface and substrate properties
 - Skepticism concerning some contemporary theories of heat island causality, including urban-rural thermal properties, supposed reduced urban evaporation rates & pollution effects on the incoming longwave irradiance
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Preface [3]

- Themes in Oke's first publications:

- The problem of determining the heat storage flux in urban areas
 - Issues in adapting standard micrometeorological methods of eddy flux measurement to the city, including spatial heterogeneity, definition of the urban "surface", flux constancy with height, equality of eddy diffusivities and advection (eddy covariance deemed most desirable)
 - The necessity to develop models of urban climate and its formative processes
 - Importance of *atmospheric* energy budgets (flux-divergence)
-

The Major Themes [1]

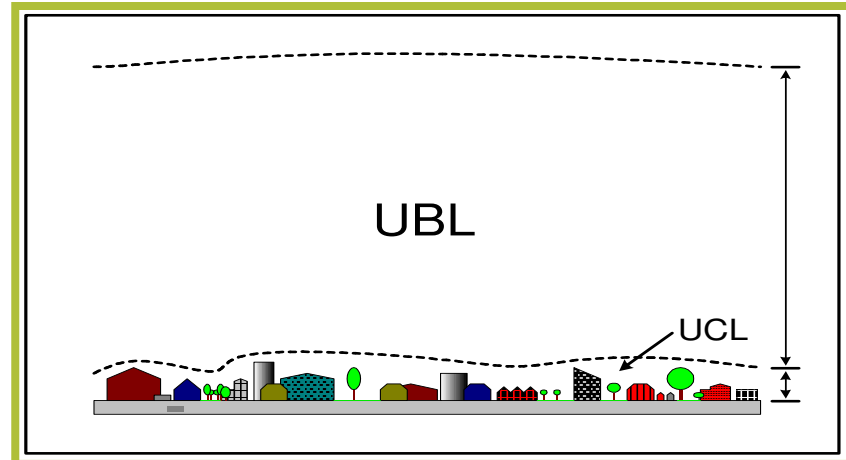
- I will present a skeleton outline of the structure and workings of the urban climate system, as we understand it today
 - I will confine topical coverage to Oke's primary areas of concentration – urban physical climatology, urban micrometeorology, urban mesoclimatology and urban boundary layer climatology
 - I will emphasize Oke's contributions (conceptual frameworks, findings, theories, methods and models), i.e. ideas:
 - initiated by Oke and pursued in his work and by others working in the field
 - adopted from the work of other urban climatologists but enhanced, expanded and advanced by Oke
 - adopted from other areas of the atmospheric science and applied in the context of the urban environment by Oke
-

The Major Themes [2]

The Urban Climate System

The distinction between the Urban Boundary Layer and the Urban Canopy Layer

- Oke (1976)
- Oke (1982)
- Oke (1988b)
- Roth, Oke & Emery (1989)
- Rotach *et al.* (2005)



More than a matter of scale: climates owe their genesis to different processes in the UBL and UCL, a different theoretical framework is needed for each and work on their coupling is imperative

- Oke (1976)
- Oke (1982)
- Nakamura & Oke (1988)

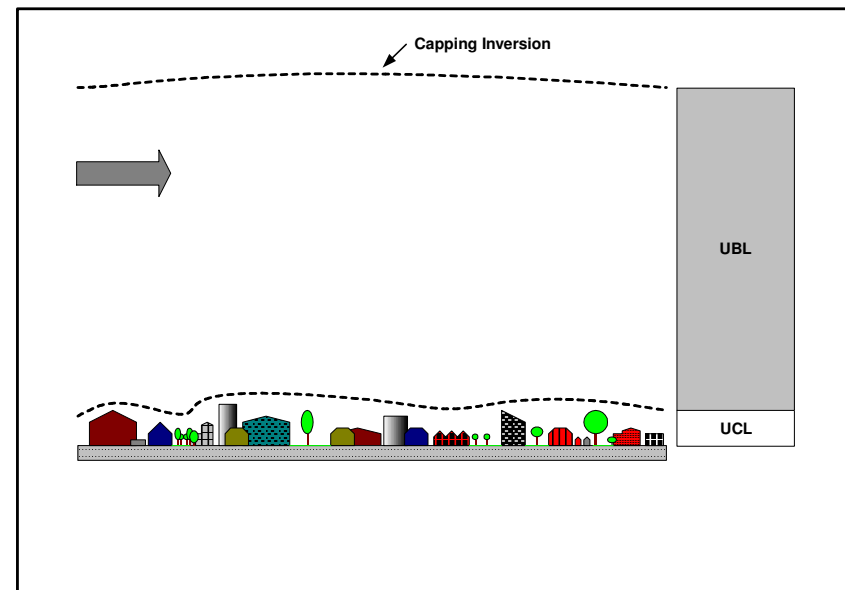
Coupling of the UCL and the UBL

- Nunez & Oke (1976)
- Oke (1976)
- Nunez & Oke (1977)
- Oke (1982)
- Nakamura & Oke (1988)
- Salmond, Oke, Grimmond, Roberts & Offerle (2005)

The Major Themes [3]

The Urban Climate System

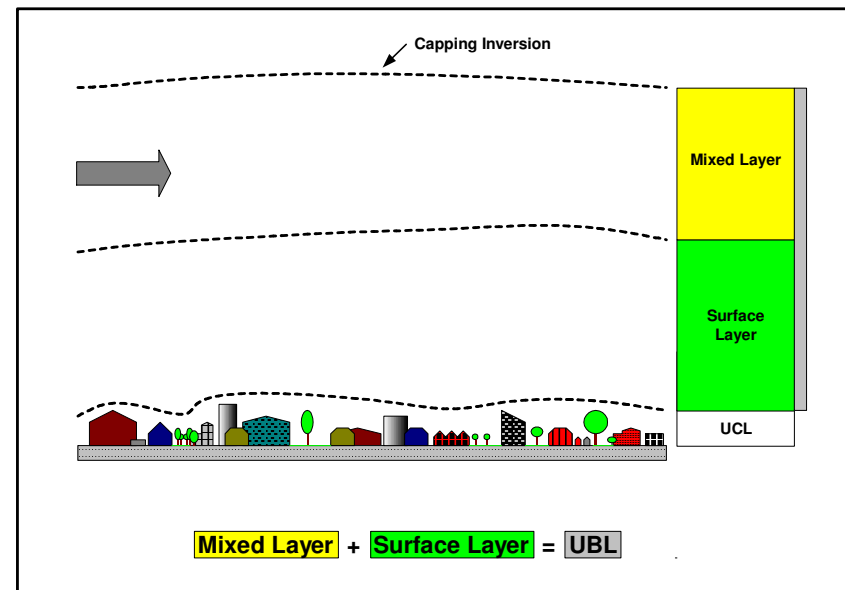
- UBL Subdivisions
 - Mixed Layer (or Outer Urban Boundary Layer)
 - Surface Layer
 - Roughness Sublayer
 - Inertial Sublayer (or Constant Flux Layer)



The Major Themes [4]

The Urban Climate System

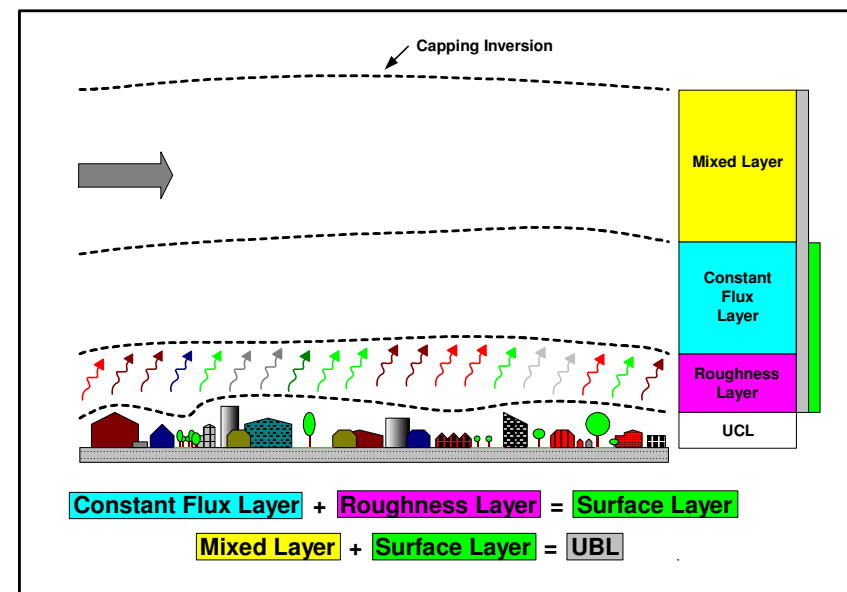
- Surface Layer



The Major Themes [5]

The Urban Climate System

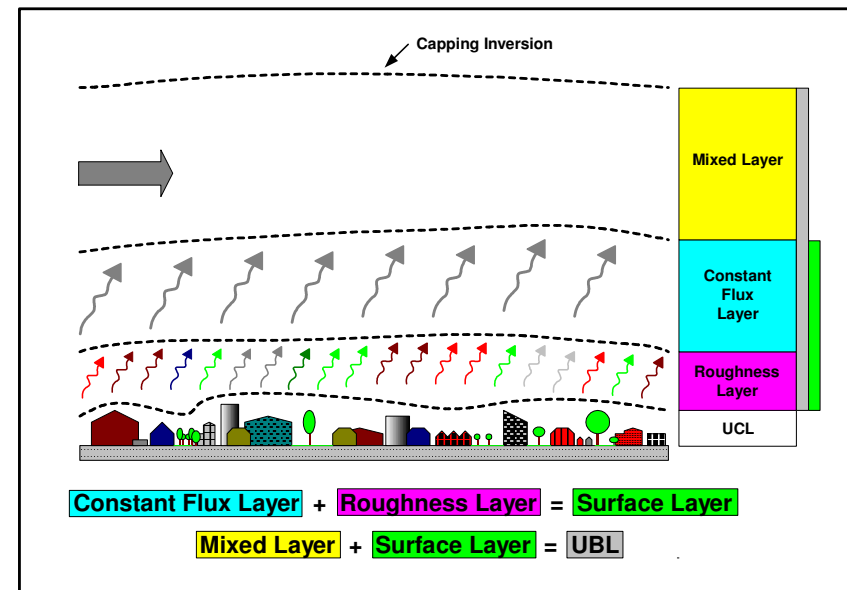
- Roughness Sublayer
 - Roth, Oke & Steyn (1989)
 - Oke, Cleugh, Grimmond, Schmid & Roth (1989)
 - Schmid, Cleugh, Grimmond & Oke (1991)
 - Roth & Oke (1993)
 - Grimmond & Oke (2002)
 - Grimmond, Salmond, Oke, Offerle & Lemonsu (2004)
 - Rotach *et al.* (2005)



The Major Themes [6]

The Urban Climate System

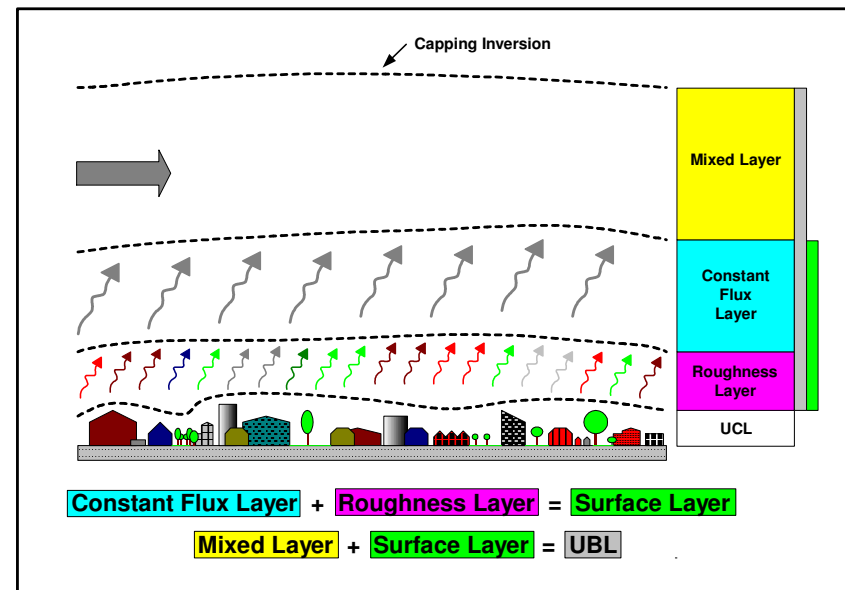
- Inertial Sublayer (constant flux layer)
 - Roth, Oke & Steyn (1989)
 - Oke, Cleugh, Grimmond, Schmid & Roth (1989)
 - Schmid, Cleugh, Grimmond & Oke (1991)
 - Roth & Oke (1993)
 - Grimmond & Oke (2002)
 - Grimmond, Salmond, Oke, Offerle & Lemonsu (2004)
 - Rotach *et al.* (2005)



The Major Themes [7]

Turbulence, Micrometeorological Theory & Measurement

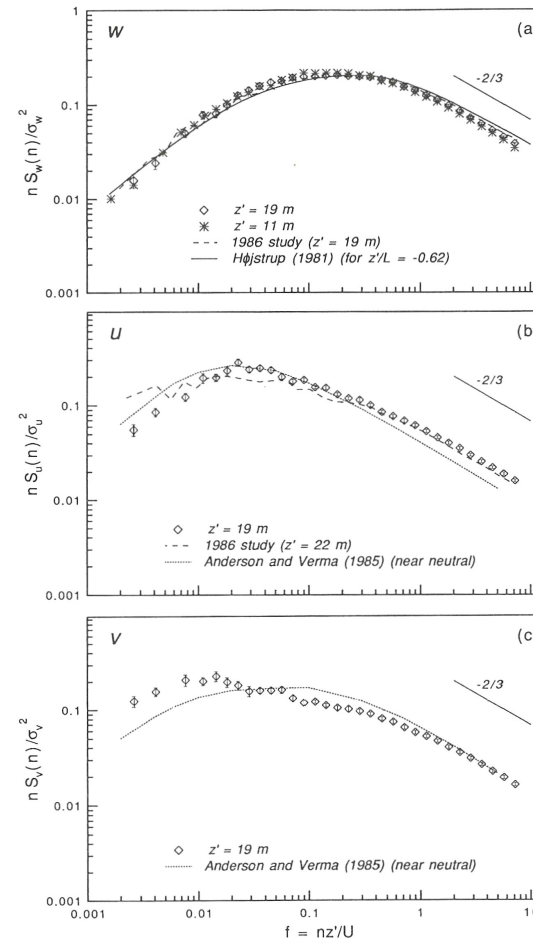
- Absence of similarity in transfer efficiencies for different entities
 - Oke (1988b)
 - Roth, Oke & Steyn (1989)
 - Roth & Oke (1993)
 - Roth & Oke (1995)
 - Kanda, Moriwaki, Suzuki, Roth & Oke (2000b)
- Applicability of Monin-Obukhov Theory in the Urban UBL
 - Oke (1988b)
 - Roth, Oke & Steyn (1989)
 - Oke, Cleugh, Grimmond, Schmid & Roth (1989)
 - Roth & Oke (1993)
 - Kanda, Moriwaki, Suzuki, Roth & Oke (2000b)



The Major Themes [8]

Turbulence, Micrometeorological Theory & Measurement

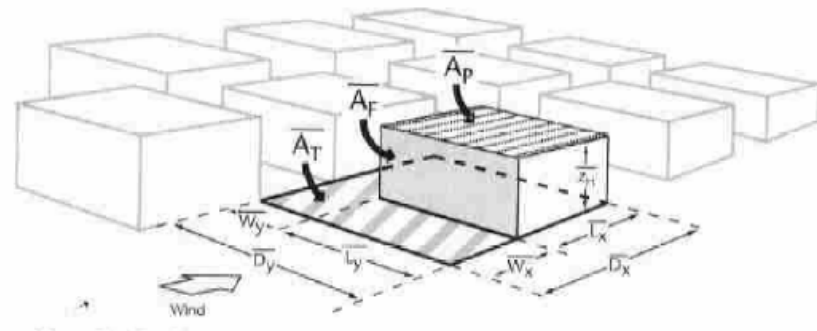
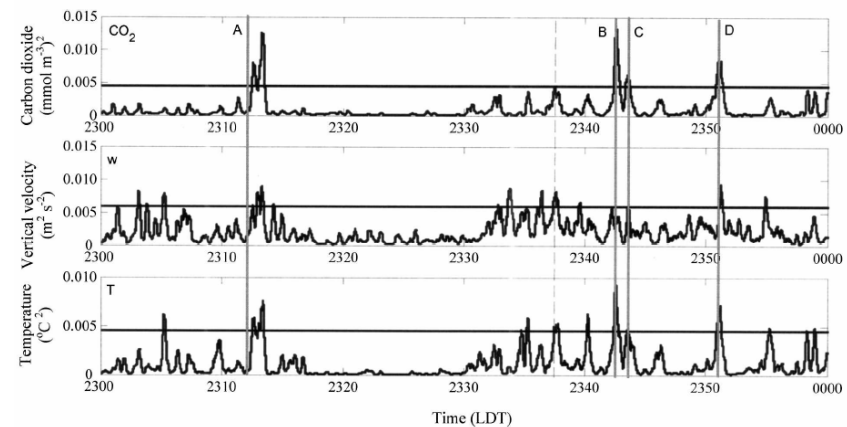
- Turbulence spectra, cospectra & other statistics over suburban terrain
 - correspondence to reference spectra
 - no evidence for spatial scales associated with the UCL
 - dissipation of TKE relatively small compared to reference cases
- Roth, Oke & Steyn (1989)
- Oke, Cleugh, Grimmond, Schmid & Roth (1989)
- Roth & Oke (1993)
- Roth & Oke (1995)



The Major Themes [9]

Turbulence, Micrometeorological Theory & Measurement

- Coherent structures in urban boundary layer (Marseille)
 - Salmond, Oke, Grimmond, Roberts & Offerle (2005)
- Aerodynamic properties of urban areas at the local scale
 - Grimmond, King, Roth & Oke (1998)
 - Grimmond & Oke (1999b)
 - Kanda, Moriwaki, Suzuki, Roth & Oke (2000a)
 - Kanda, Moriwaki, Roth & Oke (2002)



The Major Themes [10]

Turbulence, Micrometeorological Theory & Measurement

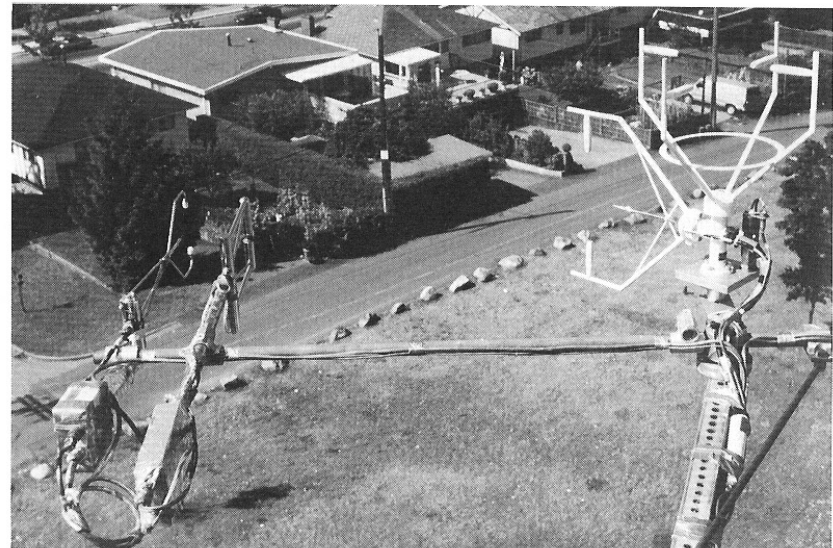
- Measurement issues for urban surfaces
 - measurement height
 - Oke (1988b)
 - Roth, Oke & Steyn (1989)
 - Oke, Cleugh, Grimmond, Schmid & Roth (1989)
 - Schmid, Cleugh, Grimmond & Oke (1991)
 - Roth & Oke (1993)
 - Rotach *et al.* (2005)
 - validity of assumptions for eddy flux measurement techniques
 - Oke (1988b)
 - Roth, Oke & Steyn (1989)
 - Roth & Oke (1993)
 - Roth & Oke (1995)
 - Kanda, Moriwaki, Suzuki, Roth & Oke (2000b)



The Major Themes [11]

Turbulence, Micrometeorological Theory & Measurement

- Measurement issues for urban surfaces
 - spatial/time sampling
 - Roth, Oke & Steyn (1989)
 - Oke, Cleugh, Grimmond, Schmid & Roth (1989)
 - Schmid, Cleugh, Grimmond & Oke (1991)
 - Roth & Oke (1993)
 - Roth & Oke (1995)
 - Kanda, Moriwaki, Suzuki, Roth & Oke (2000a)
 - Kanda, Moriwaki, Roth & Oke (2002)
 - Mestayer *et al.* (2005)

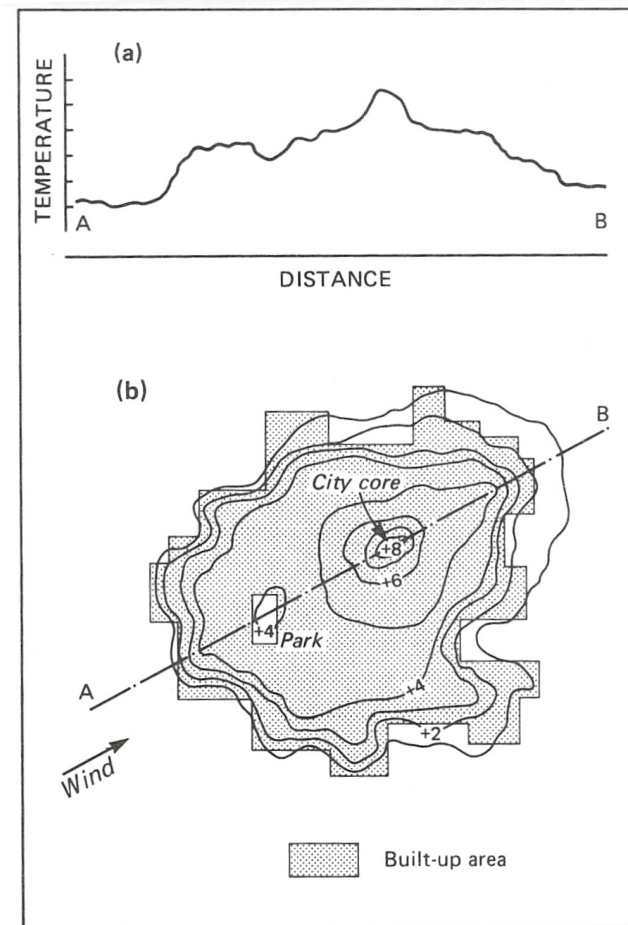


The Major Themes [12]

The UCL Urban Heat Island

UCL heat island spatial structure

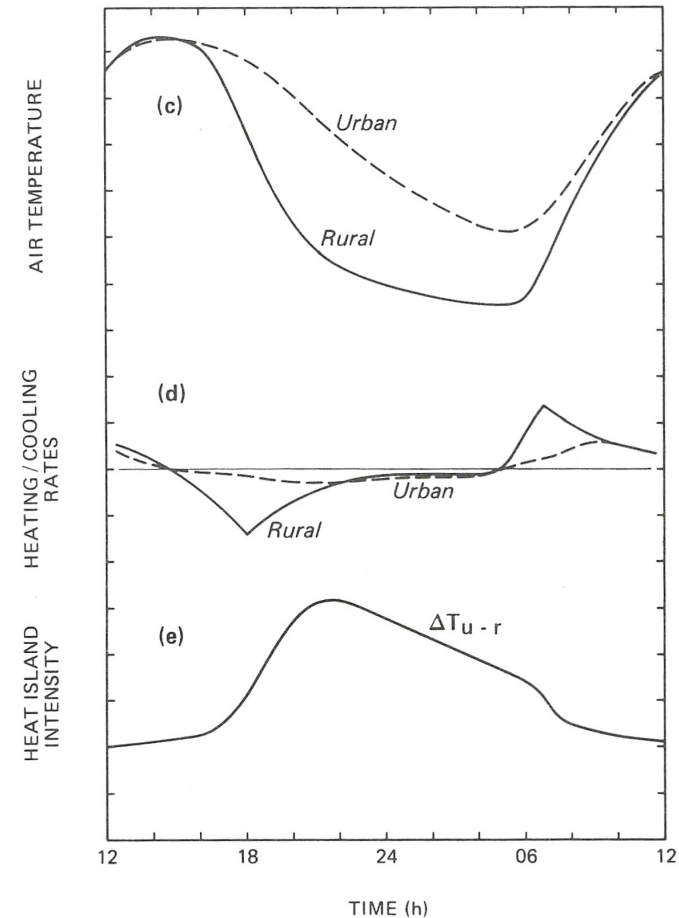
- Oke & East (1971)
- Oke (1982)
- Runnalls & Oke (2000)



The Major Themes [13]

The UCL Urban Heat Island

- UCL heat island dynamics
 - Oke & East (1971)
 - Oke & Maxwell (1975)
 - Oke (1981)
 - Oke (1982)
 - Runnalls & Oke (2000)
- Brunt cooling curve
 - Oke & Maxwell (1975)
 - Nunez & Oke (1976)
 - Oke (1981)



The Major Themes [14]

The UCL Urban Heat Island

- Oke's Proposed UCL UHI Causes (Oke, 1982)

- Increased absorption of solar radiation (canyon geometry)
 - Increased long-wave counter-radiation (air pollution)
 - Decreased net long-wave radiation loss (canyon geometry)
 - Anthropogenic heat sources (releases into canyon air)
 - Increased sensible heat storage in urban fabric (materials – thermal admittance)
 - Decreased evapotranspiration (materials - vegetated area reduction and impervious surfaces)
 - Decreased vertical mixing (canyon geometry – shelter)
-

The Major Themes [15]

The UCL Urban Heat Island

- ΔT_{u-r} dependence on wind speed
 - Oke and East (1971)
 - Oke (1973)
 - Oke (1976)
 - Oke (1982)
 - Runnalls & Oke (2000)
- ΔT_{u-r} dependence on cloud cover
 - Oke & East (1971)
 - Oke and Maxwell (1975)
 - Oke (1982)
 - Oke, Johnson, Steyn & Watson (1991)
 - Runnalls and Oke (2000)

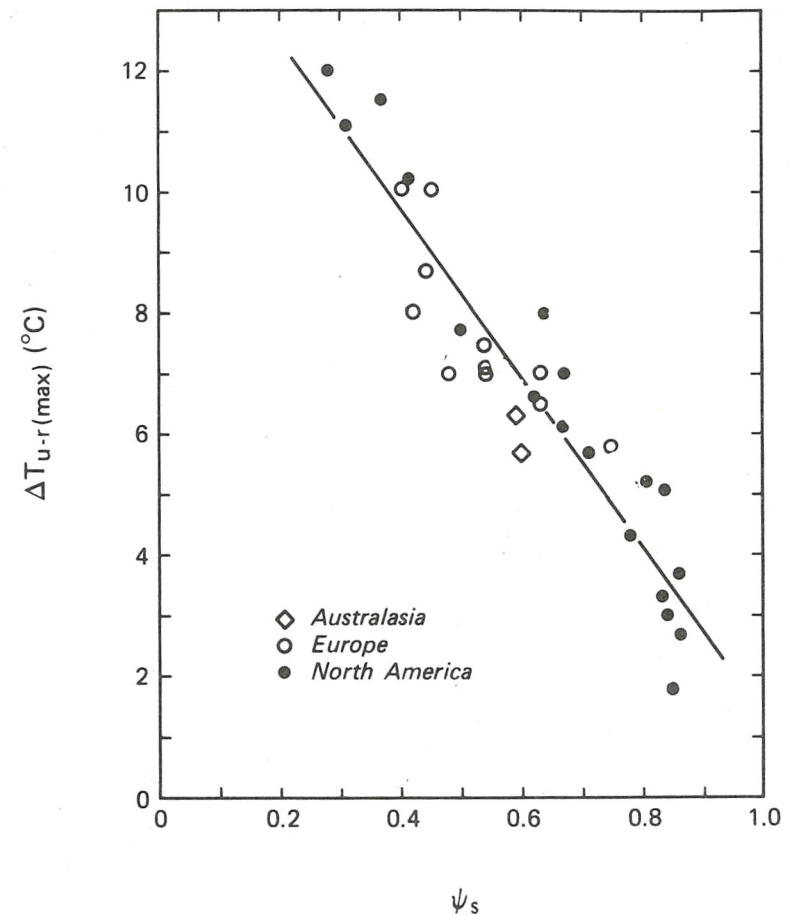
Urban heat island
intensity

$$\Delta T_{u-r} = T_u - T_r$$

The Major Themes [16]

The UCL Urban Heat Island

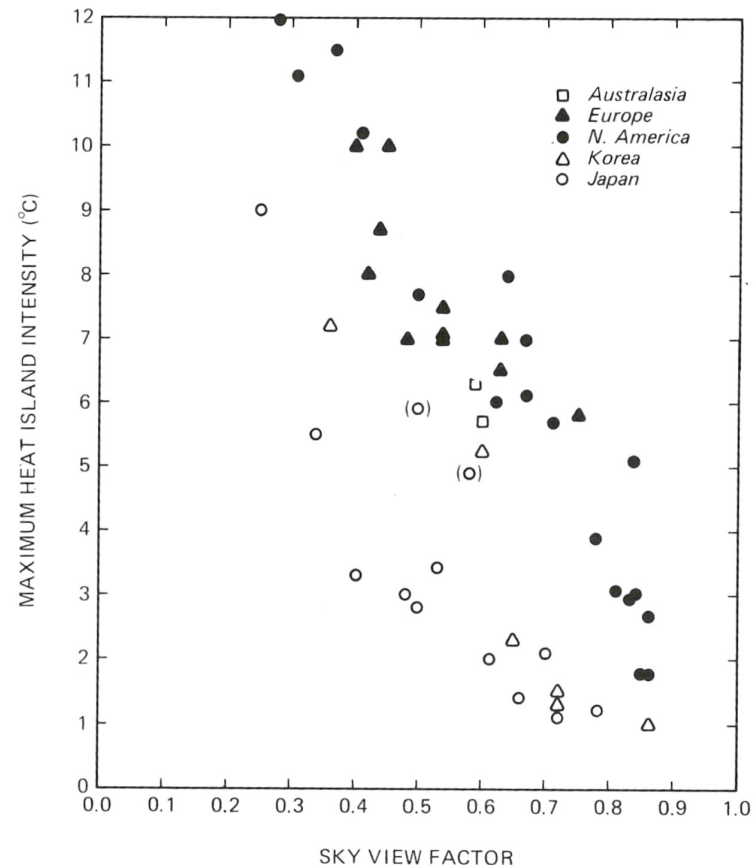
- ΔT_{u-r} dependence on urban material thermal admittance
 - Oke & Maxwell (1975)
 - Oke (1981)
 - Oke (1982)
 - Oke, Johnson, Steyn & Watson (1991)
- ΔT_{u-r} dependence on canyon aspect ratio or SVF
 - Oke (1976)
 - Oke (1981)
 - Oke (1982)
 - Oke (1988b)
 - Johnson, Oke, Lyons, Steyn, Watson & Voogt (1991)
 - Oke, Johnson, Steyn & Watson (1991)



The Major Themes [17]

The UCL Urban Heat Island

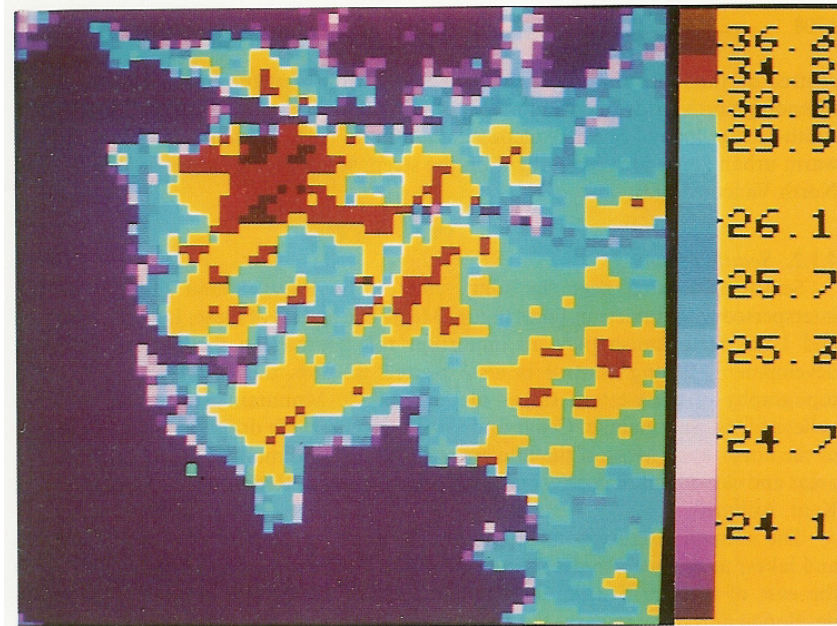
- Modelling the heat island – SHIM
 - Johnson, Oke, Lyons, Steyn, Watson & Voogt (1991)
 - Oke, Johnson, Steyn & Watson (1991)
- Simultaneous modelling of the role canyon geometry on street surface L^* , thermal admittance, anthropogenic heat and enhanced urban counter radiation due to pollution and cloud cover



The Major Themes [19]

The Surface Urban Heat Island

- Characteristics of satellite-observed surface UHIs
 - most pronounced during the day and weakest at night
 - spatial distribution of temperature closely tied to land use: peaks often associated with areas of large flat roofs and ground level paved surfaces (rather than tall buildings)
 - correlation with UCL (air temperature) UHIs often very weak (frequently negative)



The Major Themes [20]

The Surface Urban Heat Island

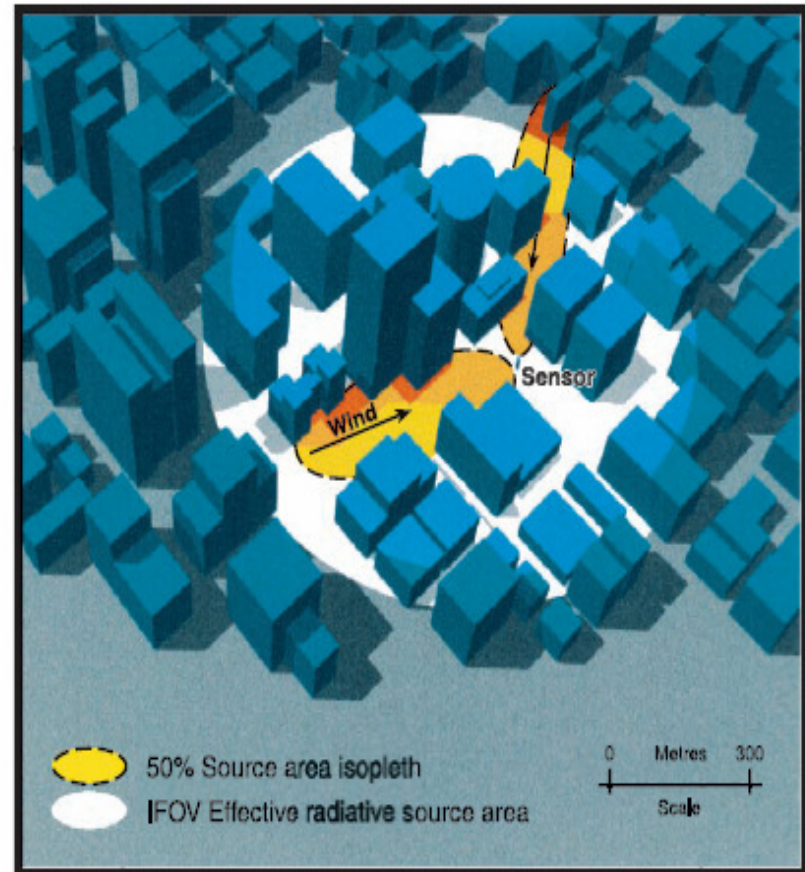
■ Roth, Oke & Emery (1989)

- What is the nature of the urban surface as “seen” by a remote sensor?
 - How do remote sensor detected radiative temperatures relate to the true air-urban interface?
 - What is the relationship between satellite-derived UHIs and those measured in air?
 - How appropriate is thermal remote sensing data as input to urban climate models?
-

The Major Themes [21]

The Surface Urban Heat Island

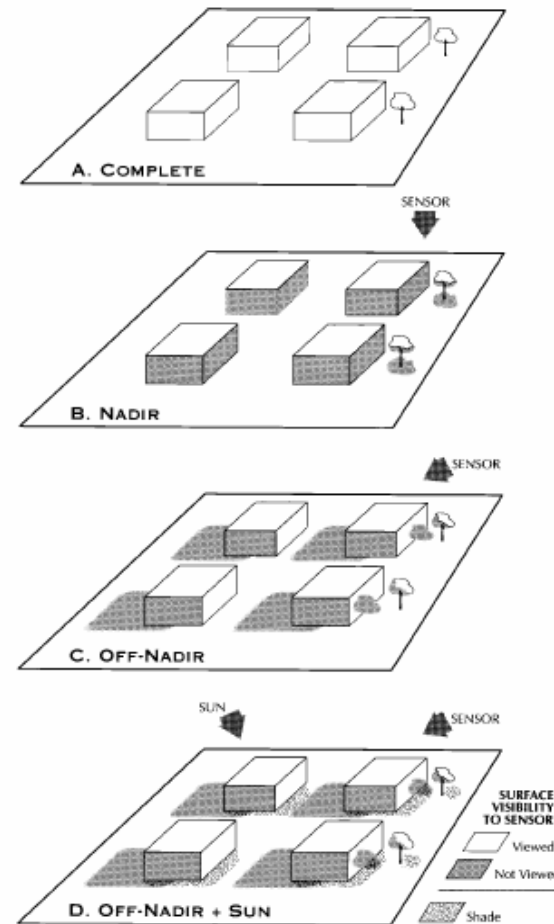
- Nakamura & Oke (1988)
- Roth, Oke & Emery (1989)
- Voogt & Oke (1997)
- Voogt & Oke (1998a)
- Voogt & Oke (1998b)
- Voogt & Oke (2003)
- Soux, Voogt & Oke (2004)
- Mestayer *et al.* (2005)



The Major Themes [22]

The Surface Urban Heat Island

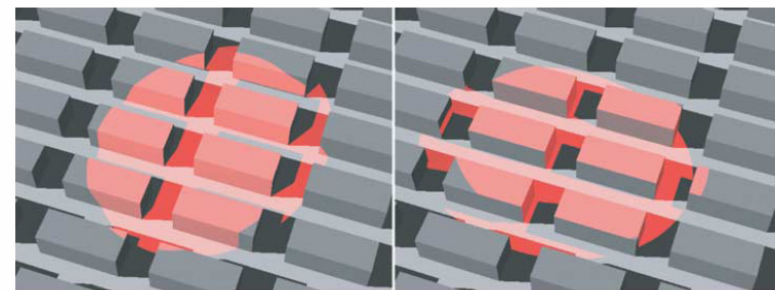
- Issues in remote sensing of the UHI
 - Nadir views oversample the horizontal facets of the urban surface and undersample vertical ones. Other sensor views give biased samples of the true urban surface temperature, depending on surface geometry and the relationship of the sun, city and sensor platform to one another.
 - “Effective anisotropy”: can lead to temperature differences of similar order to those associated with atmospheric corrections and much larger than emissivity effects, especially in zones with a regular block structure, large areas of vertical surface and with sunlit/shaded contrasts.
 - Problems in detecting true surface temperature may enhance or reduce the UHI signal.



The Major Themes [23]

The Surface Urban Heat Island

- Issues in remote sensing of the UHI
 - It is essentially futile to expect any simple relationship between remotely-sensed surface temperature and air temperatures in cities.
 - The remotely-sensed surface temperature will not, in general, equal the “complete surface temperature”: neither, in general, will it equal to “aerodynamic temperature” required for use in energy budget model calculations.
 - Modelling what a sensor “sees” of an urban area is a non-trivial problem but can yield information on what types of sensing yield a “good” sample: a “good” sample is one in which the proportions of the surface elements observed is similar to the mix contributing to the complete surface temperature.

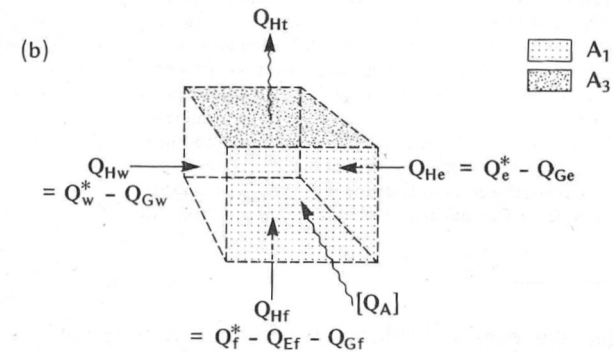
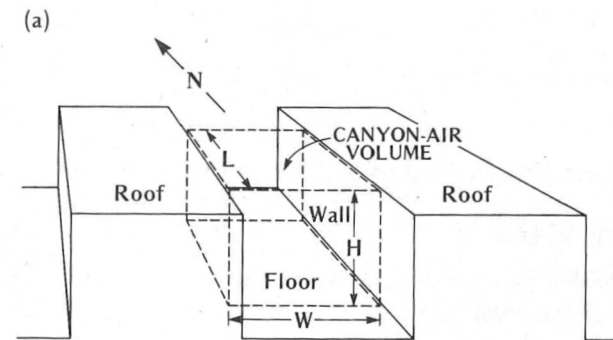


- | | |
|---------------------------|------------------|
| ■ Visible shaded wall | ■ Sunlit ground |
| ■ Visible shaded ground | ■ Sunlit rooftop |
| ■ Visible sunlit wall | ■ Sunlit wall |
| ■ Visible sunlit rooftop | ■ Shaded ground |
| ■ Visible sunlight ground | ■ Shaded wall |

The Major Themes [24]

Urban Canopy Energy Budget and Climate

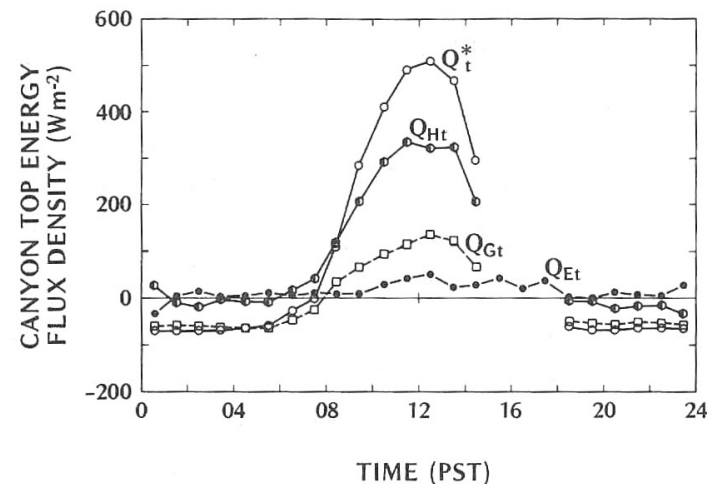
- The urban canopy comprises myriad surfaces and forms arranged in complex 3D configurations
- Typical repeating structure – the “urban canyon”
 - Nunez & Oke (1976)
 - Nunez & Oke (1977)
 - Nunez & Oke (1980)
 - Nakamura & Oke (1988)
 - Rotach *et al.* (2005)
- Oke first to formally define the urban canyon?



The Major Themes [25]

Urban Canopy Energy Budget and Climate

- Vancouver (north-south)
 - by day, Q_H is the dominant sink for Q^* for all facets, each exhibiting a unique and complex diurnal pattern driven by both incoming and reflected solar radiation
 - by night, the budget simplifies to $\Delta Q_S \approx Q^*$
 - expressed relative to the canyon top, the budget is similar to that of a horizontal surface (except for a shorter period of positive Q^*) with:
 - $Q_H \approx 0.64Q^*$, $Q_E \approx 0.10Q^*$ and $\Delta Q_S \approx 0.26Q^*$ (day)
 - $\Delta Q_S \approx Q^*$, $Q_H \approx -Q_E$
- Basel
 - Q_H through the canyon top (measured by scintillation) similar in pattern to a horizontal surface, upward-directed at night & slightly smaller in magnitude than Q_H from the adjacent roof



The Major Themes [26]

Urban Canopy Energy Budget and Climate

- Vancouver (north-south)
 - Down-canyon advection and heat transport by the mean flow through the canyon top are likely to be significant in the air volume energy budget
 - Divergence of L^* occurs during the night both across and along the canyon
 - Radiative cooling rates in the early nocturnal period exceed actual rates (suggesting Q_H convergence) but decrease later
 - Radiative cooling within the canyon is less than that at roof level and less than typical rural rates
-

The Major Themes [27]

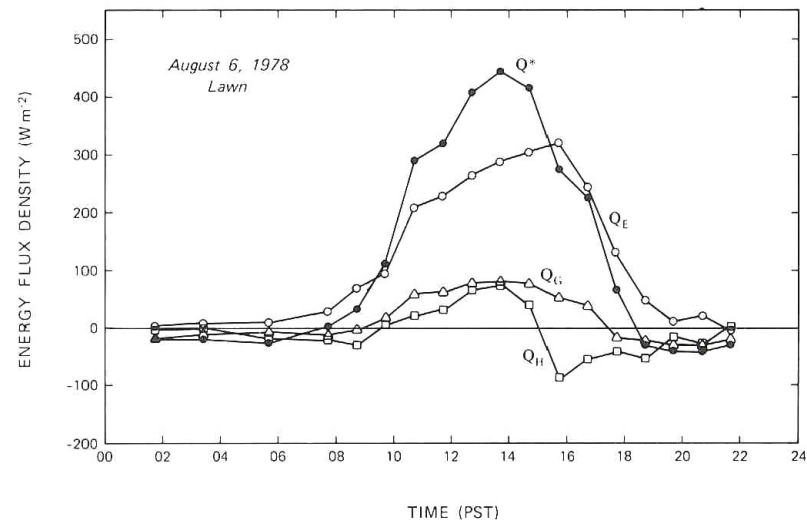
Urban Canopy Energy Budget and Climate

- Kyoto (east-west)
 - Canyon air is generally well-mixed, except within 0.5-1.0 m of the facets
 - Air temperature structure strongly conditioned by solar irradiation patterns
 - Roof air is slightly warmer than canyon air by day and cooler by night but differences are small
 - Evidence of a vortex within the canyon with a “corkscrew” pattern with ambient diagonal winds
 - Cross-canyon flow gives the strongest temperature contrasts within the canyon and along-canyon flow the least
 - The air within the canyon is unstable at all times, including the night
-

The Major Themes [28]

Urban Canopy Energy Budget and Climate

- Irrigated lawn (Oke, 1979)
 - Q^* peaked by day and only moderately negative at night (skyline obstruction)
 - Q_E dominates the energy budget and exceeds Q^* for much of the afternoon and evening (inversion and downward-directed Q_H)
 - Q_E enhanced by sensible heat advection at the micro-scale from surrounding warm impervious surfaces



The Major Themes [29]

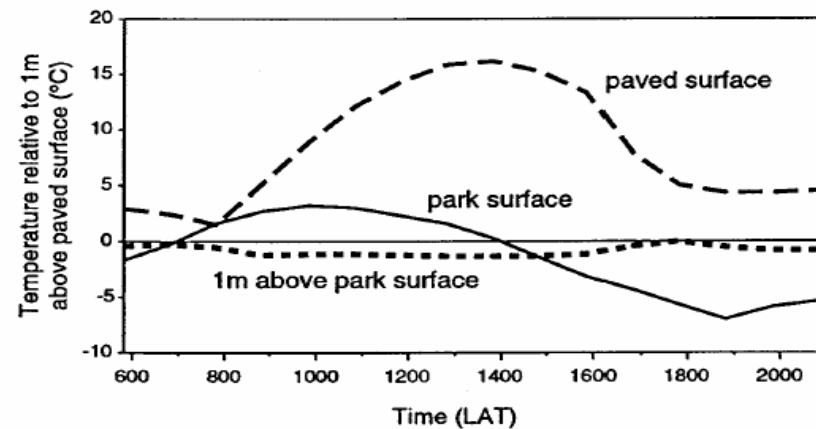
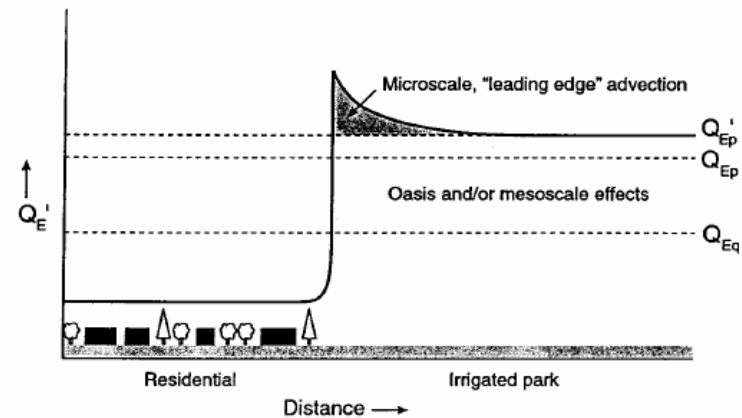
Urban Canopy Energy Budget and Climate

- Urban parks (Spronken-Smith & Oke, 1998, 1999)
 - Park “cool islands” based on surface temperature may be large with temperatures variable by park type.
 - Cool islands defined with respect to air temperature are more muted, rarely more than 3°C cooler than built-up surroundings, into which lower temperatures may be advected about one park width
 - Scale modelling suggests that, as with canyons, both SVF and thermal admittance of materials are contributory to the degree of coolness of a park
 - Edge effects (warmer surface) extend about 2.2X-3.5X the height of the park border into the park
 - A park large enough to build up a cool air pool may initiate a centripetal circulation that will extend the cooling into the adjacent built-up area
 - Moist parks with tree cover may be cool by day but may exhibit retarded cooling at night (thermal admittance and SVF): evaporation may indirectly play a role in cooling parks at night by starting cooling from a lower temperature at sunset
-

The Major Themes [30]

Urban Canopy Energy Budget and Climate

- Irrigated urban park (Spronken-Smith, Oke & Lowry, 2000)
 - Greatest evaporative enhancement at upwind edge (leading edge effect) with $Q_E > Q^*$
 - In park centre, Q_E smaller but also $> Q^*$ in afternoon (oasis effect)
 - Q_H directed towards the surface (inversion)
 - *Thermostat-effect*: irrigated park behaves analogously to a wet leaf in a hot environment (Sacramento) – surface temperature never gets more than a couple of degrees above air temperature and is below it for much of the day

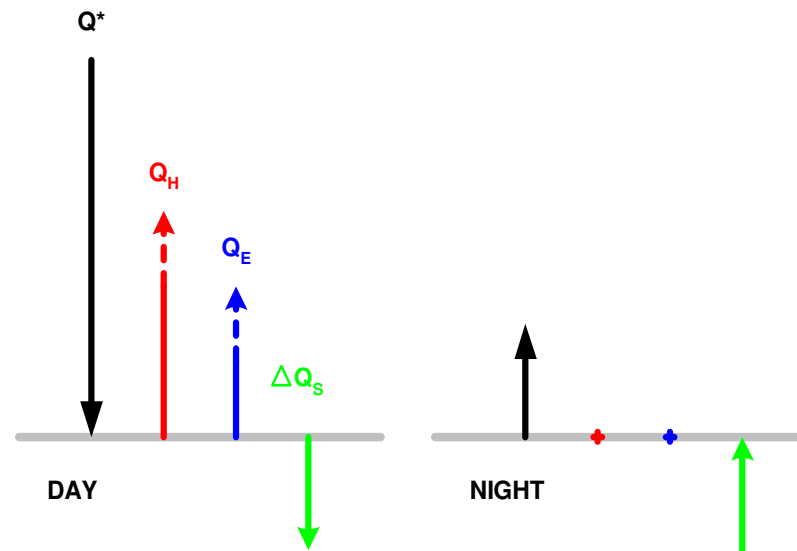


The Major Themes [31]

Local-Scale Urban Surface Energy Budgets

■ Residential-Suburban Sites

- Kalanda, Oke & Spittlehouse (1980)
- Oke (1982)
- Oke & McCaughey (1983)
- Cleugh & Oke (1986)
- Grimmond & Oke (1986)
- Oke (1988b)
- Schmid, Cleugh, Grimmond & Oke (1991)
- Grimmond, Oke & Cleugh (1993)
- Roth & Oke (1994)
- Grimmond & Oke (1995)
- Grimmond & Oke (2002)



The Major Themes [32]

Local-Scale Urban Surface Energy Budgets

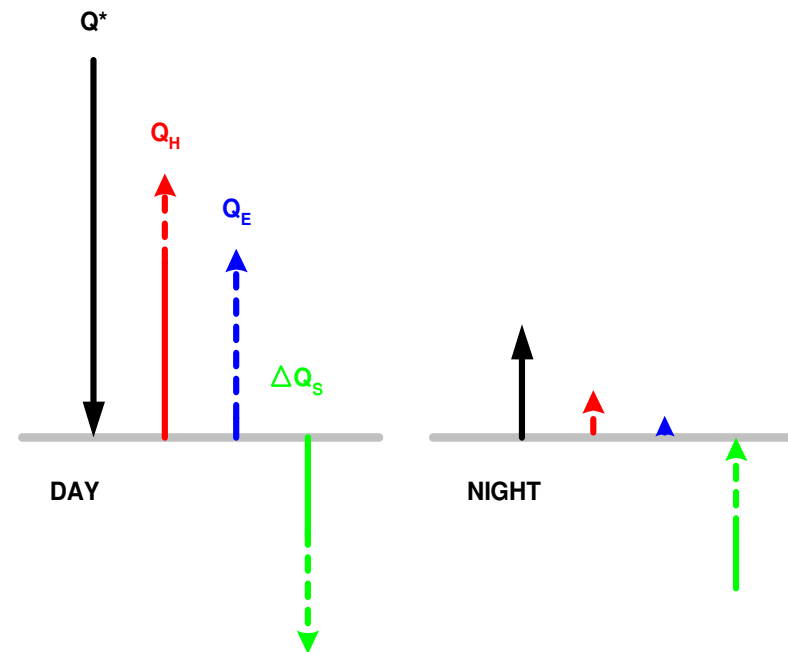
■ Residential/Suburban Sites

- Very little spatial variability in Q^* over suburban areas
- Q_H usually the largest daytime sink, often asymmetric around solar noon, showing a long “tail” to midnight
- Q_E larger than might be expected based on vegetated fraction (although not as high as early studies suggested), perhaps:
 - maintained by piped water supply
 - enhanced by micro-scale advection and oasis effects for small moist surface patches
 - augmented under appropriate synoptic conditions by mesoscale advection acting through entrainment of dry air brought about by roughness-induced mechanical turbulence (strong coupling with PBL)
- “Rebound” in evaporation rate during extended dry periods after 4-6 days, attributable to perceptual lag of homeowners and correlation between piped water supply use and evaporation rates
- Correlation between Bowen ratio and area irrigated.
- Marked variation in partitioning between the turbulent fluxes on a day-to-day basis – attributed to synoptic variability and PBL coupling
- ΔQ_S exhibits marked hysteresis (flux larger in morning than afternoon)
- Afternoon decline in ΔQ_S supports the Q_H “tail” until late in the evening

The Major Themes [33]

Local-Scale Urban Surface Energy Budgets

- City Centre & Industrial Sites
 - Oke, Zeuner & Jauregui (1992)
 - Oke, Spronken-Smith, Jauregui & Grimmond (1999)
 - Grimmond & Oke (2002)
 - Grimmond, Salmond, Oke, Offerle & Lemonsu (2004)
 - Mestayer *et al.* (2005)
 - Lagouarde, Irvine, Bonnefond, Grimmond, Oke, Salmond & Offerle (2005)
 - Offerle, Grimmond, Fortuniak, Klysiak & Oke (2005)
 - Rotach *et al.* (2005)



The Major Themes [34]

Local-Scale Urban Surface Energy Budgets

■ City Centre & Industrial Sites

- Daytime budget dominated by sensible heat fluxes (Q_H and ΔQ_S each dominate in different cities)
- Q_H asymmetric with a peak after solar noon and long “tail” through afternoon and evening, to upward-directed flux at night
- Scintillometry generally confirms Q_H magnitudes but with smoother diurnal regime attributed to better spatial sampling compared to eddy covariance method
- ΔQ_S is far larger than typical for suburban sites (and for most rural sites), peaks before solar noon, declines through the afternoon, goes negative before the net radiation, and provides a source of heat to maintain an upward directed sensible heat flux at night
- ΔQ_S exhibits marked hysteresis (flux larger in morning than afternoon)
- Q_E :
 - often larger than expected on the basis of restricted greenspace but usually the smallest energy budget component
 - seems to depend on the fraction of vegetation and open water present (which can be large in some cities)
 - may be enhanced by anthropogenic sources, such as street washing, piped water leaks etc
 - may persist at low rate throughout the night
- At higher latitudes, anthropogenic heat may be relatively significant during winter when Q^* is small and may maintain turbulent fluxes in excess of the net radiation
- Variability in magnitudes of and partitioning between the turbulent fluxes between years (precipitation), seasonally and on a day-to-day basis (synoptic variability enhanced by good PBL coupling)

The Major Themes [35]

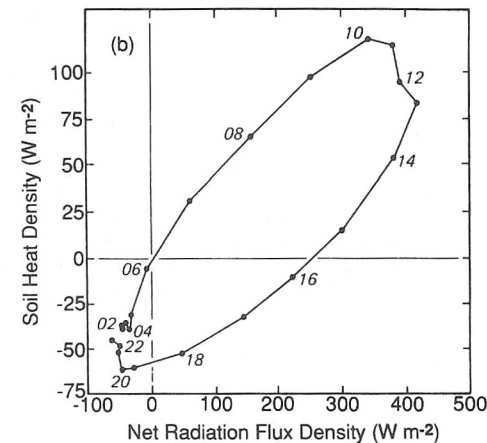
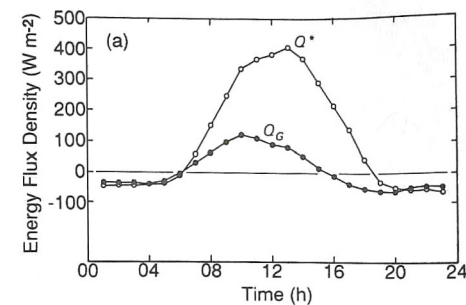
Local-Scale Urban Heat Storage (ΔQ_s) Modelling

- Oke, Kalanda & Steyn (1981)
 - Oke and Cleugh (1987)
 - Grimmond, Cleugh & Oke (1991)
 - Roth & Oke (1994)
 - Grimmond & Oke (1999a)
 - Grimmond & Oke (1999c)
 - Grimmond & Oke (2002)
-

The Major Themes [36]

Local-Scale Urban Heat Storage (ΔQ_S) Modelling

- ΔQ_S is not a negligible term in the energy budgets of urban areas (17-58% of Q^*).
- In absolute terms, ΔQ_S tends to be largest for downtown sites and smallest for residential areas.
- There exists no feasible way of directly measuring ΔQ_S : may be parameterized in terms of Q^* or found as the energy budget residual.
- Parameterizations:
 - linear regression between ΔQ_S and Q^*
 - inclusion of hysteresis between ΔQ_S and Q^* by including both Q^* and $\partial Q^*/\partial t$ as predictor variables
 - *Objective Hysteresis Model*: as above but with coefficients determined by weighting those for individual surface types (canyons, roofs, lawn, etc) according to surface fraction based on a plan area or 3D area survey



The Major Themes [37]

Local-Scale Urban Heat Storage (ΔQ_s) Modelling

■ OHM

- Generally performs well
 - Tends not to reproduce large releases of heat in the afternoon for some sites
 - Tends to underestimate the hysteresis behaviour of urban surfaces
 - Does not capture all hour-to-hour variation, possibly because it is unable to account for short-term changes in moisture conditions, wind speed variations, synoptic conditions etc, which will affect the turbulent fluxes and, hence, ΔQ_s
 - Would benefit from availability of a greater range of coefficients for more urban surface types, especially those that undergo seasonal changes in characteristics
-

The Major Themes [38]

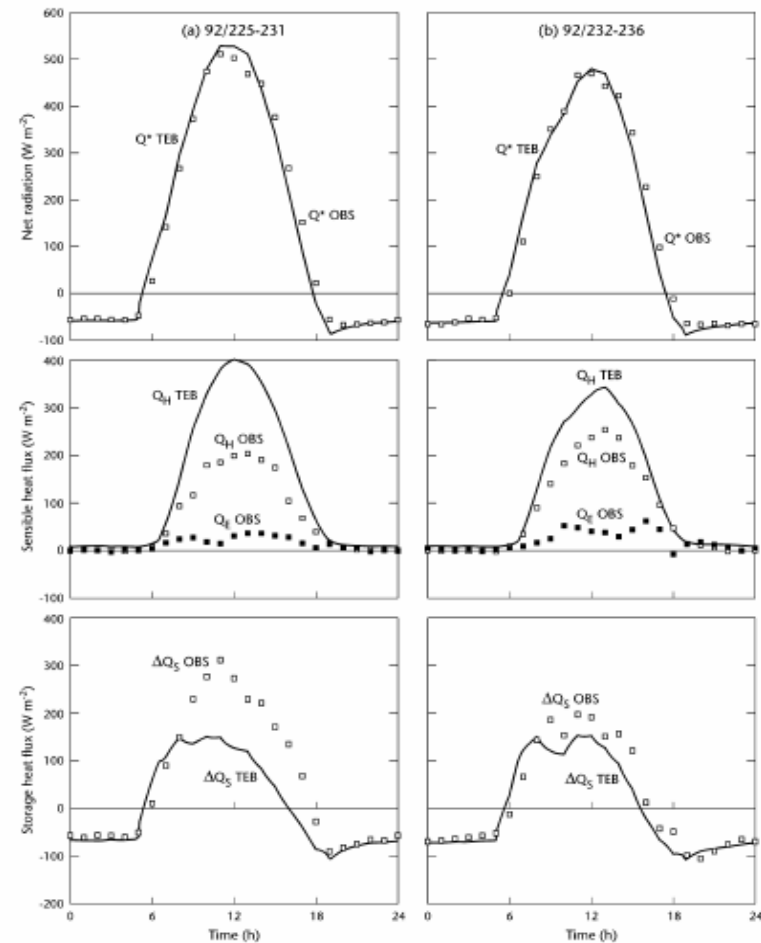
Local-Scale Urban Energy Budget Modelling

- NARP (Net All-Wave Radiation Parameterization): uses commonly available meteorological data, plus local scale emissivity and albedo information to estimate Q^* for Lodz, Chicago and Los Angeles
 - Offerle, Grimmond & Oke (2003)
 - A test of the ability of three models (Myrup, 1969; Ackermann, 1977; Carlson & Boland, 1978) to replicate measured energy budget data for the Sunset residential site in Vancouver
 - Issues in obtaining appropriate inputs
 - Q^* not excessively in error but partitioning of available energy between Q_H and Q_E very poor, primarily due to treatment of surface water availability
 - Ross and Oke (1988)
-

The Major Themes [39]

Local-Scale Urban Energy Budget Modelling

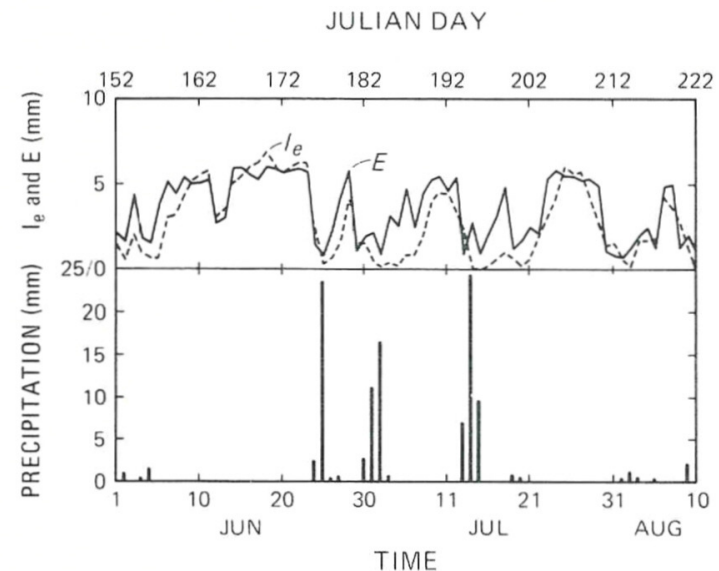
- LUMPS (Local Urban Meteorological Parameterisation Scheme): a set of equations, based on Q^* data, and using the OHM model for ΔQ_S , for partitioning the two turbulent fluxes, based on a modification of the de Bruin and Holtslag (1982) scheme
 - performs satisfactorily but requires improvements in the database of urban surface properties
 - Grimmond & Oke (2002)
- TEB (Town Energy Budget) model of Masson (2000): validation data from central Mexico City, Vancouver light industrial site and Marseille
 - performs adequately for Marseille and Mexico City but replicates $Q_H/\Delta Q_S$ partitioning less accurately for Vancouver
 - Q^* and surface temperature well reproduced for Mexico City and Vancouver
 - Masson, Grimmond & Oke (2002)
 - Mestayer *et al.* (2005)



The Major Themes [40]

Local-Scale Urban Water Budget

- Grimmond, Oke & Steyn (1986)
 - Necessity of including anthropogenic terms in the water budget for urban areas (piped water, irrigation etc)
 - Urban areas are a mosaic of patches with very different hydrological characteristics: irrigated pervious (e.g. lawns - wet much of the time), unirrigated pervious (e.g. waste ground, parks – soil moisture varies gradually with precipitation events) & impervious surfaces (e.g. roads, roofs – dichotomous “wet/dry” budgets)
- Grimmond & Oke (1986)
 - Piped water use plays a major role in the water budget of a Vancouver suburb (exceeds precipitation in many months)
 - Possesses temporal characteristics quite different from the other terms in the budget (modulated by human decision making and action, linked to geophysical events but via a perceptual filter)
 - Total amounts and temporal patterns of evaporation are consistent with the hypothesis that irrigation of gardens (from piped water) is the source



The Major Themes [41]

Local-Scale Urban Water Budget

- Oke (1989)
 - Role of urban trees in maintaining higher rates of evaporative water loss from cities than might be expected
 - Grimmond & Oke (1991)
 - Urban water budget is amenable to modelling incorporating formulations adapted from forest meteorology
 - Grimmond & Oke (1999c)
 - While evaporation may be small in some downtown and industrial areas, it can be 70-370% of precipitation for moist sites (and a much larger percentage in arid areas when nearly all available water in urban areas is piped)
 - Great day-to-day variability in evaporation rate, related to synoptic events via intense coupling of the urban surface with the PBL
 - Richards & Oke (2002)
 - Suburban dew (under appropriate synoptic conditions) forms mainly in open lawn areas and in house roofs, rather than on trees and the roadway
 - Distribution of dew on heavy dewfall nights is well explained by the SVF
-

The Major Themes [42]

Miscellany

■ The UBL

- Oke & East (1971)
- Yap & Oke (1974)
- Fuggle & Oke (1976)
- Oke (1982)
- Mestayer *et al.* (2005)

■ Urban Climate and Urban Planning/Design

- Oke (1981)
 - Oke (1984)
 - Oke (1988a)
 - Oke (1989)
-

The Oke Contribution [1]

- The Oke *opus*: remarkable as is the coherence, rigour and breadth of his work, there is, in a certain sense, an anticlimactic aspect to viewing it from the vantage point of 2006.
 - Why? Because novel and creative scientific contributions in an intellectually healthy field never seem astounding in retrospect as they become incorporated into the conceptual structure of a discipline, become routine and are adopted as a component of the shared knowledge of the field (e.g. become taught in courses on the topic) and so take on an element of the obvious.
 - Disciplines and sub-disciplines are characterised by distinctive assemblages of conceptual structures, models, methodological procedures, terminology and exemplars that define the intellectual culture of that area. Urban climatology is no exception but what is perhaps exceptional is the contribution made by one person (Oke) to the shared culture through this process of assimilation.
 - Indeed, a strong argument may be made for Oke as a “founding parent” of modern urban physical climatology and as the originator of the guiding paradigm of the field.
 - “Paradigm” is used here in Kuhn’s sense of *disciplinary matrix* rather than in his “stronger” sense and is not meant to imply adoption of the somewhat metaphysical elements of his philosophy that present the history of science as a relativistic and irrational process (scientific revolutions, paradigm shifts, incommensurability, and the like).
-

The Oke Contribution [2]

- What are the characteristics of the Oke work that have underpinned his role as a paradigm builder?
 - Perspective will naturally reflect my values regarding what characterizes quality, rigour and progress in the science of urban climatology.
-

The Oke Contribution [3]

- Persistent emphasis on the identification of causal processes behind urban climate phenomena and on physical understanding and insight.
 - Elevation of the methodological level within urban climate research to more effectively extract the causal relationships and enhance the richness of our understanding of urban climate phenomena.
-

The Oke Contribution [4]

Terjung's Levels of Methodology: Definitions

	Terjung (1976)	Oke (1982)	Example
1	Qualitative Inventory & Associations	Recognition & description of phenomenon	Mapping UHI & describing associations with landuse, weather etc
2	Quantitative Structural Correlations	Linkage (e.g. statistically) of the feature to other factors	Use of regression to predict UHI ΔT_{u-r} from wind speed and cloudiness etc
3	Functioning Processes	Study of processes causing the phenomenon	Measurement of Q_H , flux divergence etc
4	Physical Process-Response Systems	Construction of process-response models to predict behaviour of the phenomenon	Numerical modelling of urban SEB (e.g. TEB model)
5	Physical-Human Process-Response Systems	[not included]	As above, but with two-way linkages to social/behavioural models of humans in the city (e.g. water and energy use)

The Oke Contribution [5]

Terjung's Levels of Methodology: Oke's Publications

Time Period	Level
1971-1974	2.5
1975-1979	3.3
1980-1984	3.2
1985-1989	2.9
1990-1994	3.3
1995-1999	2.6
2000-2004	2.7
2005-2006	3.2

The Oke Contribution [6]

- The imperative to quantitative generalization: to move beyond the “case study” approach of the early days (e.g. UHI studies).
 - statistical generalization
 - mathematical modelling
 - hardware (scale) modelling
 - reduction of problems to fundamentals (e.g. process)
 - framing urban climate research results in a format suitable for users of our ideas (e.g. planners)
-

The Oke Contribution [7]

- The goal of a predictive urban climatology.
 - UCL UHI intensity magnitudes
 - canyon energy budget and climate characteristics
 - local scale urban SEBs
 - local scale water urban budgets
 - urban landscape aerodynamic properties
 - eddy flux source areas in urban terrain
 - nature of a remote sensor's sampling of urban topography
 - heat storage/release at the local scale
-

The Oke Contribution [8]

- Strength of the research programme I
 - Motivation: asking questions
 - Asking simple questions coupled intimately to a carefully formulated program of measurements focussed on answering the question
 - Asking important questions: ones to which answer will provide insight on fundamental processes operating in urban environment
-

The Oke Contribution [9]

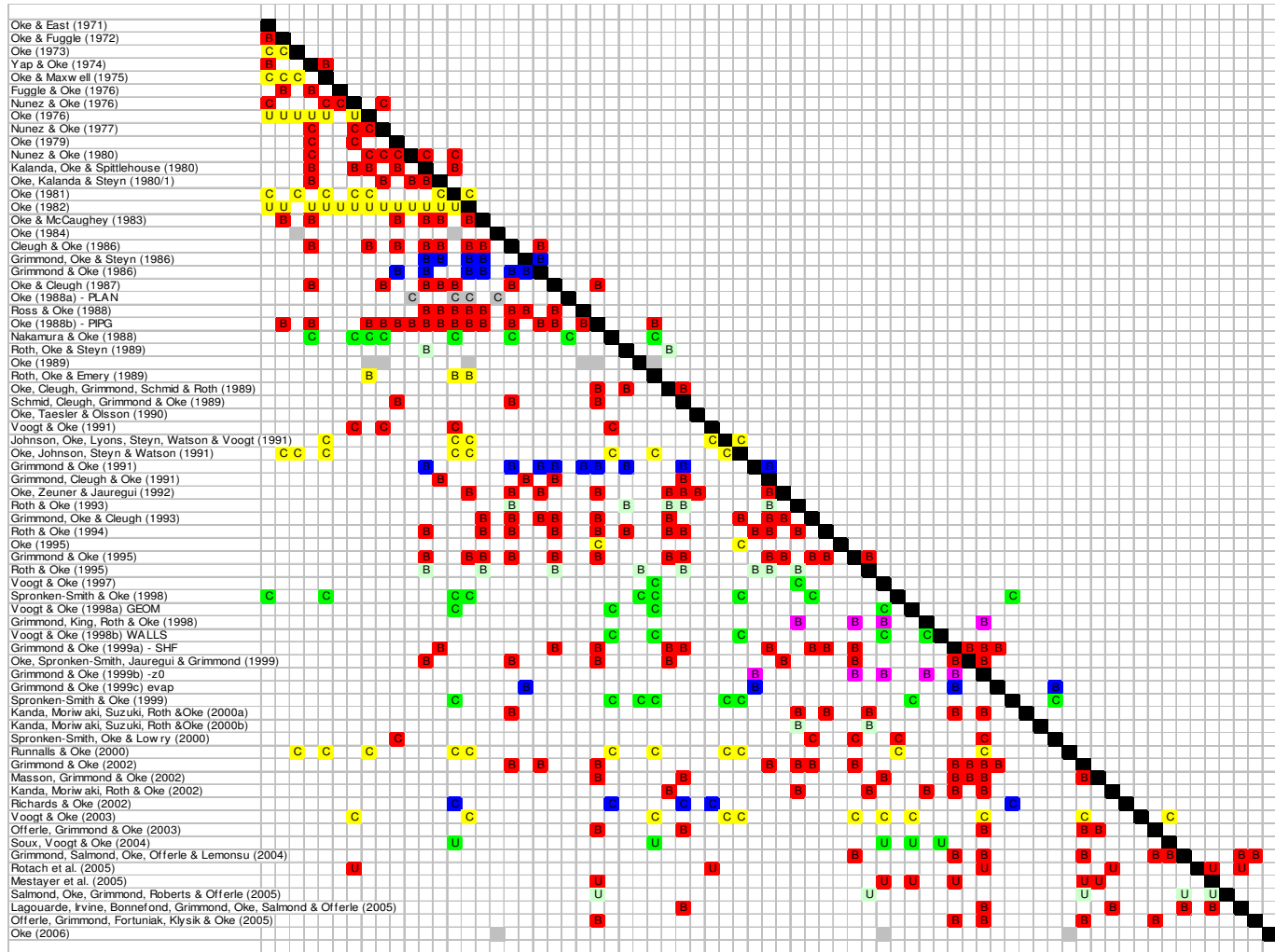
- Strength of the research programme II
 - Substantive contributions to the theoretical and conceptual framework of urban climatology
 - the UCL/UBL distinction (functioning as well as scale)
 - the distinction between different types of UHIs
 - the canyon as a repeating structure of the UCL
 - the role of the rural in defining “urban climate”
 - application of forest meteorology concepts in novel ways within urban climate
 - the concept of the canopy
 - tower-based measurement techniques for areally-averaged fluxes
 - methods to estimate heat storage flux
 - precipitation interception
 - evaporation from sparse heterogeneous systems
 - roughness layer depth over rough surfaces
 - synoptic scale advection effects
 - the importance of scale (again, not just size but process!)
-

The Oke Contribution [10]

- Strength of the research programme III
 - Coherence of the body of work
 - The citation matrix



The Oke Contribution [11]



The Oke Contribution [10]

- Strength of the research programme III
 - Coherence of the body of work
 - Citation matrix
 - Persistence of themes identified in 1968-1969 *McGill Climatological Bulletin* articles
 - Explicit posing of research questions for future work
 - Importance of the need for high quality observations: sensor error analysis, instrument exposure, time and space sampling issues etc.
-

The Oke Contribution [1 1]

- Beyond the science – subdisciplinary “citizenship”
 - Broad scope of understanding and encouragement of diverse approaches (e.g. collaboration between observational and modelling scientists, particularly emphasis on appropriate forms of model validation)
 - “Ambassador” for urban climatology to cognate disciplines (e.g. urban planning/design)
 - Mentoring (both students and colleagues)
 - Seeking to upgrade and enhance the status and content of, and internal communications within, urban climatology (e.g. Oke, 2006)
-

Postscript



- “The central objective of my research is to elucidate the physical basis of the human impacts on climate caused by urban development. It requires understanding the exchanges and balances of heat, mass and momentum as they are modified from those of the pre-urban landscape to their present state. This means working across a range of atmospheric scales (from micro- to mesoscale) and relating the modification of these processes to the climatic effects they evoke.”
 - (T.R. Oke, <http://www.geog.ubc.ca/~toke/ResearchProjects.htm>)
-