Urban Temperatures and Urban Heat Islands

- James Voogt
- Associate Professor & President International Association for Urban Climate
- Western University, London ON Canada

Part 2: Urban Heat Islands

- Beginnings – heat island types
- Conceptual basis – Lowry approach.
- Physical basis for UHIs: Relating UHIs to temperature changes and the energy balance
- UHIs in the future
Heat Island Types

a) Mesoscale

Roughness sublayer

Canopy Layer Heat Island (CLUHI)

Surface Heat Island (SUHI)

Modified after Oke (1997)

Urban Heat Islands

Types

Sub-types

AIR

UBL (BLUHI)

- Fixed
- Traverse
  - tower, sodar
  - aircraft, tetroon

UCL (CLUHI)

- Fixed
- Traverse
  - screen
  - automobile

SURFACE (SUHI)

- ‘True’ 3-D
  - complete surface
- Bird’s-eye
  - 2-D T°
  - aircraft, satellite
- Zero-plane
  - T°
  - model output
- Ground
  - T°
  - road

Substrate

Depends on definition of ‘surface’

After Oke (1995)

Modified after Oke (1997)

AS1: Urban Climate
School of Architecture, The Chinese University of Hong Kong, Hong Kong, 7-11 Dec 2015
Finding Urban Effects: Lowry Conceptual Model

\[ M_{itx} = C_{itx} + L_{itx} + H_{itx} \]

- \( M \): measured value of a weather element (e.g. temperature)
- \( C \): background ("flat-plane") climate
- \( L \): departure from \( C \) due to topography
- \( H \): departure from \( C \) due to human effects (including urban effects)

Subscripts:
- \( i \): weather type
- \( t \): time period
- \( x \): station location (see 'Zones' next slide)

Lowry (1977)

Defining Zones in the Lowry Model

\( u \) – urban area
\( r \) – rural or natural area*
\( e \) – a rural or natural area surrounding the urban area that is influenced by urban effects

*Rural areas are impacted by human activities such as agriculture; natural areas have none (i.e. \( H_{itx} = 0 \))

Consider temperature measurements in these zones.

Lowry (1977)
Utility of the Lowry Framework

a) shows that measurements (e.g. temperature) in a city have contributions from multiple influences.
b) demonstrates that a reference location outside the urban area may not be fully free of human influences
c) provides a framework for experimental design and control related to identifying urban effects

A difficulty is that the framework has many assumptions that are difficult to fully satisfy

What is the Urban Effect?

• We want to isolate $H$ for an urban site

Conceptually: $M_{10x} = C_{10x} + L_{10x} + 0$, so $M_{1tx} - M_{10x} = H_{1tx}$

But... pre-urban measurements are typically not available and $C$ may change over time.

• An alternative: numerical model for the same site run without the urban area
Urban – “Rural” Differences

\[ M_{itu} - M_{ite} = (C_{itu} - C_{ite}) + (L_{itu} - L_{ite}) + (H_{itu} - H_{ite}) \]

Is \( M_{itu} - M_{ite} \) evidence of urban effects?

Issues:
What is area e and can it be determined \textit{a priori}?
Is area r a good representation of pre-urban conditions?
Note that area e may be large from some climate variables

The Lowry model and UHI assessment

• A UHI is an urban effect – the Lowry model provides a conceptual basis for identifying urban effects that is important to making UHI measurements (e.g. siting instruments)

• Lowry model is useful for many other urban effects and is applicable to modeling approaches as well as observations
Physical Basis for Heat Islands

• Urban heat islands are created by differences in urban and rural energy balances.

• Consider the physical basis of the main UHI types

Land use areas with large amounts of visible impervious surfaces appear hot during the day (Warehouse, Lt industrial).
Large diurnal temperature range.
At night large and positive SUHI, maximum at end of night.
Diurnal Evolution of Urban Surface Temperature


Surface Temperature Changes

- Temperature change can be related to the surface energy balance
- By day we have

\[ C \frac{\partial T_0}{\partial t} z = Q^* - Q_H - Q_E - Q_G \]

- \( C \) is heat capacity of a very thin layer of depth \( z \)
**SUHI: daytime surface heat exchanges**

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

Canyons

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

**SUHI: nighttime surface heat exchanges**

Canyons
Urban & Rural Surface Temperature Changes

Night time SUHI: Important controls

- SVF $\psi_s$: sky view factor
- $\mu$: thermal admittance
- Largest SUHI occur with small SVF, small rural $\mu$, large urban $\mu$
SUHI Temporal Variability

Urban-Rural Temperature for Cities Grouped by Biome

F – Forest, G – Grassland, D – Desert, M – Mediterranean Forest

Imhoff et al. (2010)

Canopy Layer Heat Islands

• Canopy Layer: UHI is a maximum at night, under calm and clear conditions (max 12°C, annual average 1-2°C). May be small or even negative during the day.

Oke (1982)
Unlike SUHI 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°.
• Clearly CLUHI is due to thermal inertia - difficulty in warming and cooling

Voogt and Oke (unpublished)

Differences in urban & rural cooling underly the CLUHI

Important differences in the early morning and near sunset

AS1: Urban Climate  School of Architecture, The Chinese University of Hong Kong, Hong Kong, 7-11 Dec 2015
CLUHI temporal intensity

Oke (1982, 2011)

Temperature Change in a Layer

\[
\frac{\partial T_a}{\partial t} = \frac{1}{C_a} \left( \frac{\partial Q^*}{\partial z} + \frac{\partial Q_H}{\partial z} \right) = \frac{1}{C_a} \left( \text{div} Q^*_z + \text{div} Q_{H-z} \right)
\]

Oke (1987)

Simplified situation: large, flat, homogeneous surface
No net horizontal transfers.
No latent heat release.
By day, when atmosphere well mixed, \( \text{div} Q^*_z \approx 0 \)
Temperature Change in a Volume

\[ \frac{\partial T_a}{\partial t} = \frac{1}{C_a} \left( \text{div} Q_v + \text{div} Q_{H,v} \right) + \bar{u} \frac{\partial T}{\partial x} \]

for both radiation and sensible heat flux consider the \textit{volumetric} divergence

\[ \text{div} Q = \frac{\partial q}{\partial x} + \frac{\partial q}{\partial y} + \frac{\partial q}{\partial z} \]

e.g. Stull (1988; 2015)

**CLUHI: daytime heat exchanges**

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

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

\[ \text{Air} - T_{a \text{ roof}} > T_{a \text{ canyon}} \quad \text{CLUHI - small: } \overline{T_{a \text{ urban}}} - \overline{T_{a \text{ rural}}} \]

_Oke et al. Urban Climates; forthcoming, Cambridge University Press_
CLUHI: heat exchanges at night

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

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

**Air - T<sub>roof</sub>** < T<sub>canyon** CLUHI - large, positive:** T<sub>urban</sub>** > T<sub>rural</sub>

References:
- Oke *et al.* Urban Climates; forthcoming, Cambridge University Press

---

**Volume Processes: Night – Clear and Calm**

**Urban**
- Weak -div*Q*<sub>vy</sub>, radiation from canyon walls; stronger div*Q*<sub>v</sub> (but not as strong as in rural area due to sky view factor obstruction)
- Weak -div*Q*<sub>Hy</sub>: heat from canyon walls
- Net result: radiative cooling that is weaker than for the rural case

**Rural**
- Strong radiative divergence \( \text{div } Q^*\)_v under stable night time conditions
- Weak sensible heat flux convergence -div*Q*<sub>H</sub> from above
- Net result, strong radiative cooling
Maximum UHI vs Surface Controls

Sky view factor, $\psi_s$

Canyon aspect ratio, $H/W$

Oke (1981), and $H/W$ Oke (1987)

Seasonal Variation of Rural Soil Thermal Admittance

$U_{H,I,UCL, Pot} = U_{H,I,UCL, Obs} / [u^{-2/5} (1 - kn^2)]$

Runnalls and Oke (2000)
Temporal Evolution of Canopy Layer Heat Island

Note:
- Daily pattern
- Seasonal pattern with daylength
- Seasonal effects of prevailing weather and rural surface conditions

Plotted by T.R. Oke with data from Klysik and Fortuniak Łódź, Poland 1997-1999

When is the canopy layer heat island best developed?

Heat island intensities for Vancouver from 1991-1994

Runnalls and Oke (2000)
Weather Controls on the CLUHI

Cloud cover relation
n = fraction of cloud cover
k = coefficient based on cloud type
k larger for thick low clouds

Combined Effects:
“Weather Factor $\Phi_w$”
$\Phi_w = u^{-0.5} (1 - kn^2)$
$\Phi_w$ how much will UHI be reduced from its maximum potential value; $0 \leq \Phi_w \leq 1$.

(Runnalls and Oke 2000)
Boundary Layer Urban Heat Islands

- Increased absorption of $K_\downarrow$ by air pollutants.
- Anthropogenic Heat ($Q_H$) - heat production by space heating, particularly stacks.
- Increased $Q_H$ from below (heat flux from roof tops and canopy layer).
- Increased $Q_H$ from above (increased roughness leads to increased turbulent entrainment).

Modified after Oke (1997)
Control of Urban Form on the Heat Island

<table>
<thead>
<tr>
<th>Urban Form Characteristic</th>
<th>Impact on Heat Island</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surface geometry</td>
<td>Low SVF promotes high night time CLUHI. Shading reduces daytime SUHI and CLUHI.</td>
</tr>
<tr>
<td>Surface reflectance</td>
<td>High reflectance reduces all daytime HI, with some effects continuing to the nighttime HI</td>
</tr>
<tr>
<td>Surface thermal properties</td>
<td>Materials that are good “storers” of heat will contribute to night time CLUHI, BLUHI and potentially to negative daytime cool islands. Some materials that are well insulated (e.g. roofs) may contribute to daytime SUHI and BLUHI due to their high temperatures.</td>
</tr>
<tr>
<td>Greenspace</td>
<td>Reduces all daytime heat island and possibly night time heat island depending on the exact nature of the vegetation used (e.g. trees vs grass).</td>
</tr>
<tr>
<td>Irrigated areas</td>
<td>Strong reduction of daytime SUHI, CLUHI with some transfer to BLUHI</td>
</tr>
</tbody>
</table>

Based on Oke (1982)

Heatwaves and Cities

European Heat Wave: 55,000 deaths
Russian Heat Wave: 70,000 deaths

The urban heat island can magnify heat wave effects

Heat is the deadliest of weather hazards (US Data)
Future Changes to UHI

- With large scale climate change, CLUHIs both increase and decrease

McCarthy et al. (2010)

Factors Affecting Heat Islands

- **Geographic Location**
  - climate
  - topography
  - rural surrounds

- **City Size**
  - fetch distance
  - density of use

- **City Form**
  - materials (fabric)
  - structure
  - cover

- **City Function**
  - energy use
  - water use
  - pollution

- **Time**
  - day
  - season

- **Synoptic Weather**
  - wind & cloud
  - stability

- **Mitigation Measures**

"manageable"

Oke (pers. comm.)
Summary

• Lowry conceptual model is useful for thinking about how to measure and interpret urban heat islands and all urban measurements.
• Urban actions to address heat islands should recognize the different types and their specific processes.
• Physical basis of the urban heat island is rooted in energy balance differences that differentially affect urban and rural heating and cooling rates at the surface and in the UCL or UBL air volume.
• Cities of the future are likely to be hotter but the UHI may not necessarily be larger depending on how rural cooling rates are affected.

End, Thank you

James Voogt
Department of Geography
Western University,
London ON Canada N6A 5C2
Tel: 519-661-2111 x85018
Email: javoogt@uwo.ca
Website:
http://www.geography.uwo.ca/people/faculty/voogt_james.html