How Researchers Measure Urban Heat Islands

James Voogt
Department of Geography,
University of Western Ontario
London ON Canada
Outline

- What is the urban heat island?
- What types of urban heat islands exist?
- A conceptual basis for measurements.
- Boundary Layer Heat Island – direct or remote measurement
- Canopy Layer Heat Island – direct measurement
- Surface Heat Island – remote thermal measurement
- Modelling Heat Islands – numerical, empirical and scale modelling approaches
What is an Urban Heat Island?

- **urban heat island**—(Or heat island.) Closed isotherms indicating an area of the surface that is relatively warm; most commonly associated areas of human disturbance such as towns and cities.

  The physiographic analogy derives from the similarity between the pattern of isotherms and height contours of an island on a topographic map. Heat islands commonly also possess “cliffs” at the urban–rural fringe and a “peak” in the most built-up core of the city. The annual **mean temperature** of a large city (say $10^6$ inhabitants) may be $1{}^\circ–2{}^\circ$C warmer than before development, and on individual **calm, clear** nights may be up to $12{}^\circ$C warmer. The warmth extends vertically to form an urban heat dome in near calm, and an urban heat plume in more windy conditions.

What is an Urban Heat Island?

- When we use the term urban heat island, we are usually referring to the relative warmth of air temperature near the ground (canopy layer).
- UHI form in the air due to a difference in cooling between urban and rural areas.

Oke (1982)
Urban Heat Islands: Three Main Types

- Boundary Layer Heat Island
- Canopy Layer Heat Island
- Surface Heat Island

Modified after Oke (1997)
Addition of anthropogenic heat from chimneys and vents.

Addition of heat from roofs and tops of urban street canyons.

Absorption of solar radiation by low reflectance surfaces and trapping by reflections.

Impermeable surfaces – reduced surface moisture and evapotranspiration.

Obstructed view of sky: trapping of radiation heat by surfaces.

Addition of anthropogenic heat, humidity and pollutants.

Insulated surfaces lead to high daytime surface temperatures.

Winds slowed, turbulence increased.

Warmer, more polluted urban boundary layer.

Rough urban surface slows winds.

Increase of stored heat by thermal properties of urban materials and increased surface area.
A Conceptual Model for Urban Climate Measurements

\[ M_{i,t,x} = C_{i,t,x} + L_{i,t,x} + U_{i,t,x} \]

- \( M \) - measured value of a weather element
- \( C \) - background ("flat-plane") climate
- \( L \) - departure from \( C \) due to topography
- \( U \) - departure from \( C \) due to urban effects

Subscripts:
- \( i \) - weather type
- \( t \) - time period
- \( x \) - station location (urban, environs, rural)

Recognizes that a measured element is impacted by influences at a number of different scales – the trick is to try and isolate urban influences.

Lowry (1977)
Factors Affecting Urban Heat Islands

Geographic Location
- climate
- topography
- rural surrounds

City Size
- linked to form and function

City Form
- materials
- geometry
- greenspace

City Function
- energy use
- water use
- pollution

Time
- day
- season

Synoptic Weather
(Limits UHI)
- wind
- cloud

Mitigation Measures

Oke (pers. comm.)
UHI Types and Measurement Approaches

### Types
- **UBL (BLUHI)**
  - Fixed tower
  - Traverse aircraft
  - Remote sodar
- **UCL (CLUHI)**
  - Fixed screen
  - Traverse automobile
  - Standard grass
  - Non-Standard roof, roadside
- **SURFACE (SUHI)**
  - True 3-D (Complete)
  - Bird’s-eye 2-D aircraft, satellite
  - Ground road
  - Zero-plane model output

### Sub-types
- **AIR**
- **SUBSTRATE**

*Modified after Oke (pers. comm.)*

**BLUHI Boundary Layer Urban Heat Island**
**CLUHI Canopy Layer Urban Heat Island**
**SUHI Surface Urban Heat Island**

*depends on observation method*

*depends on definition of the surface*
Boundary Layer Urban Heat Island Measurements

- **Tower** – temperature sensors mounted on tall towers in urban and rural regions
  - Sensors must be kept well away from tower:
    - 10 tower diameters for open towers
    - Two boons: 3x structure diameter for solid towers
- **Tethered balloons** – profiles of temperature (subject to aviation, wind, storm restrictions)
- **Radiosondes** (“free” balloons) – profiles of temperature (may be aviation restrictions)

Note that at least two towers, balloons or radiosondes are required to identify a UHI

- **Traverse** – aircraft-mounted temperature sensors flown across an urban area
Boundary Layer Urban Heat Island Measurements

- SODAR: sound detection and ranging – can be problems with urban deployment
  - Background noise
  - Noise for residents
- Microwave radiometers
- RASS: radio acoustic sounding system
- Ceilometer (LiDAR)

Emeis et al. (2004)
Helsinki Testbed
(7 January 2006)

Rural: Mäntsälä

Downtown Helsinki

Urban: Valilla

Source: Muenkel and Dabberdt, Vaisala
Boundary Layer Urban Heat Islands

Day

Night

Oke (1982)
Boundary Layer Temperature Profiles from a Microwave Radiometer

Zvenigorod: suburban; Moscow: urban

Khaikine et al. 2006
Networks of sensors at standard or screen-level (~1.3 m)
- Network design should consider the Lowry (1977) conceptual model – particularly with respect to locating urban and rural sites.
- Sensors must be adequately shaded and ventilated in order to provide reasonable measurements
- Sensor location is critical in urban environments
  - What are the measurements trying to represent?
  - What is the sensor source area – the surface type upwind of the measurement site?
  - Are there multiple rural – non-urban types surrounding the city?
Urban Measurements: Assess Local Scale Surroundings

- Urban climate zone
- Dominant land-use
- Topography
- Roughness Class
- % of land cover veg/built/water/open
- Tree & building ht
- Irrigation
- Typical building materials
- Space heating/cooling
- Anomalous heat sources
- Traffic density

WMO/Oke (2006)
Urban Measurements: Assess Microscale Surroundings

Sensor heights
Surface cover
Soil/materials under cover
Building types and materials
Roof types
Urban Climate Zone
Roughness class
Changes

WMO/Oke (2006)
Corrections required for temperature changes during the time of the traverse – at least the start and end-points must be common. Assumption of linear cooling may be inadequate.


Consider spatial vs temporal sampling – variations in vehicle speed influence number of observations (e.g. over representation of intersections?)

The source area of the sensor should be considered – not necessarily representative of larger land use area.
Canopy Layer Urban Heat Islands

- Canopy Layer: heat island 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.

Aguado and Burt (2004)

Oke (1982)
Traverses of a Canopy Layer Urban Heat Island

- UHI magnitude small in daytime, grows through the night
- Note differences in temperature *ranges*

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Vancouver, Clear late summer (August) day

SN = Solar Noon, SS = Sunset

Voogt (2000)
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
Surface Urban Heat Island Measurement

Tokyo – dense housing and Shinjuku business district

- Thermal remote sensing – uses non-contact instruments that sense longwave or thermal infrared radiation to estimate surface temperature.
- Clear weather limitation (for satellites)
- Spatial view of the urban surface (although not all surfaces seen)
- Relative temperature measurement – for comparison between images may require correction for atmospheric and surface effects

Vancouver - urban area on a coastal delta with mountains (top), sea (left) and farmland (to right and bottom)
Definitions of the Urban Surface

- Surface definitions are important to remote sensing of urban heat island (sensors see the surface directly) and for comparing remote sensing to other measurements or model output.

Voogt and Oke (1997)
## Platforms for Thermal Remote Sensing of Urban Areas

<table>
<thead>
<tr>
<th>Platform</th>
<th>Sample Image</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Satellite</td>
<td><img src="image1.png" alt="Satellite Image" /></td>
<td>Extensive spatial coverage; temporal coverage may be limited. Impacted by weather and atmosphere. Spatial resolution may be limited.</td>
</tr>
<tr>
<td>Aircraft</td>
<td><img src="image2.png" alt="Aircraft Image" /></td>
<td>Higher resolution, more detail of urban features. High cost, irregular coverage. Non-standardized product.</td>
</tr>
<tr>
<td>Ground-based</td>
<td><img src="image3.png" alt="Ground-based Image" /></td>
<td>May provide unique perspective of some urban features. Possibility of high temporal resolution, can avoid corrections due to atmospheric influence.</td>
</tr>
</tbody>
</table>
Some Platforms/Sensors used for Thermal Remote Sensing

- Satellite (spatial and temporal resolution for thermal band sensors)
  - GOES (4 km – up to once every 15 min)
  - AVHRR (1.1 km – daily global coverage - two passes per day)
    MODIS (1 km – global coverage every 1-2 days)
  - Landsat (120 or 60 m - 16 day repeat coverage)
  - ASTER (90 m - 16 days)
- Aircraft/Thermal scanner (spatial resolution depends on sensor and aircraft altitude)
- Ground-based/Infrared Thermometer (spatial resolution – determined by sensor and sensor distance from surface)
Surface Temperature

*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)
Surface Urban Heat Island (SUHI) is large both day and night.
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.
Radiative Source Areas: What does a remote sensor “see”?

White outline: IFOV of a thermal remote sensor (but not all surfaces are seen within the circular outline)

Yellow ellipse: source area for a thermometer measuring air temperature

Thermal remote sensing instruments are “line of sight” instruments.

When using thermal remote sensing to view an urban surface, recognize that:

1) Not all surfaces will be viewed (often a bias to a “bird’s eye” view)

2) The “source area” for the remote sensor may not match that of other sensors on the ground (that have source areas that depend on wind direction, height of the sensor and atmospheric stability and turbulence.)

*Voogt and Oke (2003)*
Urban Surface and Air Temperatures

The surface influences the overlying air but shows much larger spatial variation, particularly in daytime. Surface modifications influence the atmosphere downwind of the source.

Modified from Spronken-Smith and Oke (1998)
Modelling Urban Heat Islands

- **Numerical** (using computer code) – ranges from very simple (spreadsheet based) to highly complex (CFD)
- **Empirical** (statistical) – based on collective observations and/or model simulations
- **Scale models**: outdoor or indoor

http://www.cv.titech.ac.jp/~kandalab/COSMO/COSMO.html

Town Energy Balance Model (Masson 2000)
Empirical: statistical relations derived from observations (or sometimes model output) that provide an estimate of heat island magnitude (usually maximum heat island)

\[ \Delta T_{u-r(max)} = 15.27 - 13.88 \text{ SVF} \]
Numerical Modelling of Urban Heat Islands

Boundary Layer Heat Island

Canopy Layer Heat Island

AIR

Zero-plane model output

Canopy and above canopy layers model output

Multi-layer model output

SURFACE (SUHI)

True 3-D (Complete – requires 3-D model)

Canyon Components roof, wall, road (e.g. TEB)

Flat Plane set to urban thermal/radiative characteristics

Krayenhoff et al. (2003)

Ashie et al. (2005)

Krayenhoff pers. comm.
Numerical Modelling of Urban Heat Islands

- Representation of the urban surface may vary from very simple to highly complex. Single or multiple atmospheric and subsurface layers may be used.
- Model may be run “off-line” (forced by observations) or embedded as part of a larger scale weather model (forecast)
- Consider the output levels of the model – for matching with observations.

Lemonsu et al. (2006)
Further Reading

- Urban Heat Islands (General)
  Mills, G. 2004. The Urban Canopy Layer Heat Island
  Available from: http://www.urban-climate.org/

- Observation Methods
  Oke, T.R. 2006. Initial Guidance to Obtain Representative Meteorological
  Observations at Urban Sites. World Meteorological Organization, Instruments and
  Observing Methods, IOM Report No. 81, WMÖ/TD-No. 1250
  Kadygrov, E.N. 2006. Operational Aspects of Different Ground-Based Remote
  Sensing Observing Techniques for Vertical Profiling of Temperature, Wind,

- Urban Remote Sensing

- Urban Modelling
  Theoretical and Applied Climatology, 84(1-3), 35-45.

- MIST Heat Island Tool: http://www.heatislandmitigationtool.com/