Surface Urban Heat Island effect
by Thermal Remote Sensing

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The Urban Heat Island (UHI) effect refers to cities being warmer than their rural surroundings because of the built environment absorbing, retaining, and/or producing more heat than the natural landscape it replaces (Oke, 1982)

$$UHI = T_{\text{AIR URBAN}} - T_{\text{AIR RURAL}}$$

Remote sensors operated in thermal infrared wavelength region have been used to observe the Surface Urban Heat Island (SUHI).

$$SUHI = LST_{Urban} - LST_{Rural}$$
Big cities: Washington, Shanghai, Tokyo, etc,
From 30-80 years, Tmax summer increases 0.5 °C each 10 years…

Cities are already suffering the impacts of global warming
More than 3 °C

Today, 55% of the world's population (74% Europe) lives in urban areas (4.4 billions) another 2.5 billion people to urban areas by 2050
Impacts

The impacts can be negative or positive depending on the climate and the time of year:

<table>
<thead>
<tr>
<th>Impact</th>
<th>Cold weather region</th>
<th>Warm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Human-health comfort</td>
<td>Positive (winter) Negative (summer)</td>
<td>Negative (four stations)</td>
</tr>
<tr>
<td>Energy consumption</td>
<td>Positive (winter) Negative (summer)</td>
<td>Negative</td>
</tr>
<tr>
<td>Air pollution</td>
<td>Negative</td>
<td>Negative</td>
</tr>
</tbody>
</table>

The risk of death is multiplied by 6 for each degree of TST increases during a heat wave**


Summer 2003 Paris

5,000 deaths due to heat stress Paris, 1-15 August 2003

- Chicago (July 1995): 600 deaths caused by heat wave
- Moscú (August 2010): mortality from 370 to 700
This image of Earth’s city lights was created with data from the Defense Meteorological Satellite Program (DMSP) Operational Linescan System (OLS). Originally designed to view clouds by moonlight, the OLS is also used to map the locations of permanent lights on the Earth’s surface.

*World urbanization prospects, 2011., United Nations, Department of Economic and Social Affairs
Simulated Night Lights

Image: H-J Schellnhuber

2070

Founding Director, Potsdam Institute for Climate Impact Research;
red colour: urbanization

1987
Valencia city

2009
The annual number of tropical nights ($T_{\text{min}} > 20.0 \, ^{\circ}\text{C}$) at the airport and at the city centre (Viveros)

- Significant increasing trend in mean temperature (0.23 $^{\circ}\text{C}$ per decade) between 1906 and 2014
- The number of warm days and warm nights increased, while the number of cool days and cool nights decreased
- The occurrence of cold spells drastically decreased in the second part of 20th century, while warm spells have become more common after 1997.
“Dual-use European Security IR Experiment 2008”

DESIREX 2008
Contract No. 21717/08/I-LG

J. A. Sobrino (IP)

1 University of València – Global Change Unit (GCU) 2 European Space Agency (ESA), 3 Instituto Nacional de Técnica Aeroespacial (INTA), 4 Louis Pasteur University – LSIT, 5 CIEMAT, 6 University of València – Laboratory of Earth Observation Unit (LEO), 7 Universidad Autónoma Madrid (UAM), 8 Universidad Complutense Madrid (UCM), 9 Labein-Tecnalia (LABEIN), 10 Madrid City Council, 11 University of Vigo.

Participantes: 50

23 Junio al 6 julio 2008
Data acquired:

- Airborne data with the AHS sensor covering two different patterns

- Spaceborne images: ASTER/TERRA, AATSR/ENVISAT, MODIS/TERRA and AQUA, TM/Landsat, AVHRR/NOAA and SEVIRI/MSG.

- Atmospheric and ground parameters: air temperature, surface temperature, wind speed and direction, emissivity and reflectivity of urban and rural surfaces, radiation balance. (In situ measurements, fixed masts and car transects)

**DESIREX 2008 field campaign:**

- Founded by the ESA
- Coordinated by the Global Change Unit (GCU) from the University of Valencia (UVEG)
- Data acquisition in collaboration with different European teams

Oeste-Este (Pozuelo-Vallecas), Sur-Norte (Getafe-UAM). Cruzan Cibeles
Airborne Hyperspectral System (AHS) Operated by INTA

30 Flight Lines
- Time: 11h, 21h, 4h (UTC)
- Spatial resolution: 2, 4, 6 m.
- 1600, 2500, 3400 m altura
- 1000 Km longitud imagenes

80 bands
VNIR, SWIR, MIR, TIR

INTA C-212-200 EC-DUC aircraft

atmospheric transmissivity
Low flight (975 m)
Satellite altitude (700 km)
THERMOPOLIS 2009 field campaign:
• Founded by the ESA
• Coordinated by the Centre for Research and Technology Hellas (Greece)
• Ground measurements team: Global Change Unit (GCU) from the University of Valencia (UVEG)

Data acquired:
• Airborne data with the AHS sensor covering 4 different patterns (see images) and the AEROPHOTO data acquisition system.

• Spaceborne images:
  ASTER, ATSR and AATSR, MODIS, TM/Landsat, CERES, CALIPSO, AVHRR and SEVIRI.
• Atmospheric measurements.
  Vertical profile soundings, aerosol measurements
• Reference Meteorological data
  Air temperature, radiation balance
• Radiometric cal/val ground measurements (see image for the 3 cal/val points):
  surface temperature, emissivity and reflectivity of urban and rural surfaces
DATOS ATMOSFERICOS

RADIOSONDEOS
2 diarios en Barajas, measuring: Pressure, Temperature, Relative Humidity, Wind direction, Wind Speed, ...

CAUTIVOS
Coincidently with AHS flights, launched at Nuevos Ministerios. Measuring Wet and Dry Temperature, Pressure, Relative Humidity, Wind Speed and Wind direction

SODAR-RASS
Every 20 min, in the Almudena Cemetery. Measuring wind speed, wind direction, mixed layer depth, temperature, atmospheric stability
Air Temperature

AEMET:

<table>
<thead>
<tr>
<th>Station name</th>
</tr>
</thead>
<tbody>
<tr>
<td>Madrid-Parque Retiro</td>
</tr>
<tr>
<td>Madrid Barajas</td>
</tr>
<tr>
<td>Madrid-Cuatro vientos</td>
</tr>
<tr>
<td>Madrid Getafe</td>
</tr>
<tr>
<td>Madrid-Ciudad Universitaria</td>
</tr>
<tr>
<td>Madrid -Torrejón de Ardoz</td>
</tr>
<tr>
<td>Arganda</td>
</tr>
<tr>
<td>Colmenar Viejo</td>
</tr>
</tbody>
</table>

Daily evolution during DESIREX
Reflectance and Surface Temperature measured simultaneously with the airborne/satellite overpass.
Continuous measurement of Air Temperature, Relative Humidity, Wind speed and direction, Radiometric temperature

<table>
<thead>
<tr>
<th>SITE</th>
<th>UAM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rural /sub-Urban</td>
<td>UAM</td>
</tr>
<tr>
<td>Rural /sub-Urban</td>
<td>Fireman park</td>
</tr>
<tr>
<td>Urban Dense</td>
<td>CSIC</td>
</tr>
<tr>
<td>Urban Dense</td>
<td>New City Hall</td>
</tr>
<tr>
<td>Urban Dense</td>
<td>Printing</td>
</tr>
<tr>
<td>Urban Medium</td>
<td>Dpt. Cartography</td>
</tr>
</tbody>
</table>
Mobile transects. DESIREX 2008

Daily car transects in four different routes, three times per day at 4h, 11h and 22h UTC
Measurements of Air Temperature, Air Humidity and Radiometric Temperature.

Transect 1: North South
Transect 2: City Center
Transect 3: Vallecas
Transect 4: Salamanca
GROUND MEASUREMENTS

TRANSECTS WITH CARS

- Tair and Hr sonde
- Thermal Radiometer
- GPS (f=10 sec)
- Datalogger
  - Tair, Hr, Trad (f=5 sec)
Urban thermography images from different urban structures obtained during the AHS overpass
Spectral Library of representative urban surfaces was obtained.
Spectral Library of THERMOPOLIS 2009

Spectral Library of representative urban and rural surfaces was obtained.
LAND SURFACE TEMPERATURE

RADIATIVE TRANSFER EQUATION IN THE TIR RANGE (8-14 μm)

\[ L_{\lambda}^{sen} = \left[ \varepsilon_{\lambda} B_{\lambda}(T_s) + (1 - \varepsilon_{\lambda}) L_{\lambda}^{atm\downarrow} \right] \tau_{\lambda} + L_{\lambda}^{atm\uparrow} \]

\( (\lambda \rightarrow \nu) \)

Brightness temperature: \( L^{sen} = B(T^{sen}) \)

LST: \( T_s \)

B: Planck’s law
Methodology

**NDVI**

* Input: $\rho_{\text{red}}$; $\rho_{\text{NIR}}$

$$\epsilon_i = \begin{cases} 
\alpha_i + b_i \rho_{\text{red}} & \text{if NDVI} < 0.2 \\
\epsilon_v P_v + \epsilon_{bs,i}(1 - P_v) + C_i & \text{if NDVI} \geq 0.5 \\
0.99 & \text{if NDVI} \geq 0.5
\end{cases}$$


**TES**

* Input: $L_{g,TIR}$

AHS TIR channels: 72, 73, 75, 76, 77, 78, 79

$$\varepsilon_{\min} = 0.999 - 0.777 \text{MMD}^{0.815}$$


**TISI**

* Input: $L_{g,MWIR}$; $L_{g,TIR}$ night and day

$$\epsilon_j = \left( \frac{\epsilon_i}{TISI_{E_{ij}}} \right)^{\frac{n_j}{n_i}}$$

* * Becker, F. Li, Z.-L., 1990. RSE, 32.

**LST retrieval**

**Split Window**

* Input: $w$, LSE, $T_{\text{sensor}}$

$$T_s = T_i + 0.723(T_i - T_j) + 0.04275(T_i - T_j)^2 - 0.08463$$

$$+ (45.49 - 5.17w)(1 - \varepsilon) + (-60.81 + 16.93w) \Delta \varepsilon$$

* = AHS band 75

* = AHS band 79

**LSE retrieval**

All the atmosphere

Flight altitude (1860 m)

**MODTRAN**

$$L_i(T_i) = L_g i T_i + L^g$$

$$L_g i = \epsilon_i B_i(T_s) + (1 - \epsilon_i) L^g$$

$$L_g i = \frac{L_i(T_i) - L^g}{\tau_i}$$

**Input:** $\rho_{\text{red}}$; $\rho_{\text{NIR}}$

**Input:** $L_{g,TIR}$

AHS TIR channels: 72, 73, 75, 76, 77, 78, 79

$$\varepsilon_{\min} = 0.999 - 0.777 \text{MMD}^{0.815}$$

**Input:** $L_{g,MWIR}$; $L_{g,TIR}$ night and day

$$\epsilon_j = \left( \frac{\epsilon_i}{TISI_{E_{ij}}} \right)^{\frac{n_j}{n_i}}$$

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$$+ (45.49 - 5.17w)(1 - \varepsilon) + (-60.81 + 16.93w) \Delta \varepsilon$$

i = AHS band 75

j = AHS band 79
LST from AHS DESIREX

AHS LST image from TES algorithm. June 28 of 2008 at night time (composition of two patterns)

hotter areas within the city center

It corresponds to a night image and we can realize that the urban zone is warmer than its surroundings

• Land Surface Temperature (LST) and Land Surface Emissivity (LSE) have been retrieved from TIR bands by applying TES algorithm (Gillespie et al., 1998).

• Validation activities were developed successfully. For day measures the obtained validation RMSE is 3 K due to the presence of shadows. For night flights the RMSE improves obtaining a validation RMSE of 1.4 K
Figure 5. Map of LST applying TES algorithm to AHS image of 28th June 2008: (a) at noon. (b) at night.
LST maps: Intersected area DAY

Urban surface anisotropy

P01I1 Overpass (NW to SE 11:32 UTC)

Seen surfaces:
• Shadowed northern walls
• Shadowed areas south-north streets

P02I1 Overpass (S to N 11:53 UTC)

Seen surfaces:
• Sunlit southern walls
• Shadowed areas south-north streets
• Eastern walls (left)
• Western walls (right)
Urban surface anisotropy

At night the LST retrieval is less affected by the time of acquisition and the geometry of observation.

- No significant differences between both overpasses.
SUHI = $LST_{Urban} - LST_{Rural}$

Evolution SUHI from AHS LST - DESIREX

SUHI = 5 K

D 12 UTC
N 23 UTC
A 5 UTC

At noon SUHI $D < 0$
Night and Morning SUHI $N-A > 0$
• Urban-dense zone: SUHI > 0 (always)
• At night SUHI\textsubscript{urban-dense zone} is around 1-2 K lower than SUHI\textsubscript{Urban-medium dense}
• Park → Green areas mitigate the SUHI effect
Discomfort Index

\[
DI(°C) = t - (0.55 - 0.0055f)(t - 14.5)
\]

July 2nd, morning time
\( f = 32\% \)

<table>
<thead>
<tr>
<th>DI categories</th>
<th>DI temperature (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hyperglacial</td>
<td>&lt;-40</td>
</tr>
<tr>
<td>Glacial</td>
<td>-39.9 to -20</td>
</tr>
<tr>
<td>Extremely cold</td>
<td>-19.9 to -10</td>
</tr>
<tr>
<td>Very cold</td>
<td>-9.9 to -1.8</td>
</tr>
<tr>
<td>Cold</td>
<td>-1.7 to +12.9</td>
</tr>
<tr>
<td>Cool</td>
<td>+13 to +14.9</td>
</tr>
<tr>
<td>Comfortable</td>
<td>+15 to +19.9</td>
</tr>
<tr>
<td>Hot</td>
<td>+20 to +26.4</td>
</tr>
<tr>
<td>Very hot</td>
<td>+26.5 to +29.9</td>
</tr>
<tr>
<td>Torrid</td>
<td>&gt;+30</td>
</tr>
</tbody>
</table>

DI classification:
- Cold
- Cool
- Comfortable
- Hot
A supervised classification process using the *Maximum Likelihood* method as a decision rule has been considered.

**Training classes** have been defined taking into account the in-situ measurements and also by visual inspection.

The classification has been performed using at-sensor radiance values measured with the **80 spectral bands** of the AHS sensor.

**12 classes** (plus shadows) have been differentiated.

Validation: 200 independent regions results give a $\kappa$ value of around **70%**.
EMISSIVITY

Broadband Emissivities (8-13 microns)

- 0.045 - Roofs with metal
- 0.897 - Roofs with asphalt
- 0.898 - Bright bare soil
- 0.902 - Roofs with red bricks
- 0.914 - Concrete (roads, pavements & roofs)
- 0.965 - Roads with asphalt
- 0.970 - Dark bare soil
- 0.978 - Green grass
- 0.985 - Water (lakes & swimming pools)
- 0.990 - Trees
2-Julio 4:09 UTC
Rmsd: 1.2 K AEMET
The urban heat island effect in the city of Valencia: a case study for hot summer days.


SUHI-Valencia (MODIS 25-27 August 2014). 3K

High-resolution nighttime sUHI and DI during a summer night (28 June 2014).

- less comfortable areas in the densely built up city centre, main traffic arteries and industrial zones
- the urban and rural reference points need to be chosen prudently
- high-resolution satellite images with more frequent data acquisition time are needed
http://land.copernicus.eu/
http://land.copernicus.eu/global/products/lst GLOBAL (LST- 5 km)


http://climate.copernicus.eu/
http://climate.copernicus.eu/sectoral-information-system
a method to downscale climate and impact indicators to the urban scale (~1x1km²)

http://urbansis.climate.copernicus.eu/ Stockholm, Bologna, Rotterdam

http://atmosphere.copernicus.eu/catalogue/#/ aerosols (at. Correction Satellite images...)
Land Surface Temperature

The Land Surface Temperature (LST) is the radiative skin temperature of the land surface, as measured in the direction of the remote sensor. It is estimated from Top-of-Atmosphere brightness temperatures from the infrared spectral channels of a constellation of geostationary satellites (Meteosat Second Generation, GOES, MTSAT/Himawari). Its estimation further depends on the albedo, the vegetation cover and the soil moisture.

LST is a mixture of vegetation and bare soil temperatures. Because both respond rapidly to changes in incoming solar radiation due to cloud cover and aerosol load modifications and diurnal variation of illumination, the LST displays quick variations too. In turn, the LST influences the partition of energy between ground and vegetation, and determines the surface air temperature.

The Global Land Service provides the following LST-based products:
- LST: hourly LST from instantaneous observations
- LST10-DC: 10-day Land Surface Temperature with Daily Cycle
- LST10-TC1: Thermal Condition Index with a 10-day composite of Land Surface Temperature.

### LST product types

<table>
<thead>
<tr>
<th>Product version</th>
<th>Access</th>
<th>Status</th>
<th>Sensor</th>
<th>Temporal coverage</th>
<th>Spatial information</th>
<th>Timeliness</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Product portal</td>
<td>Operational</td>
<td>Imagers on-board geostationary satellites</td>
<td>2009 - present, hourly</td>
<td>Global, 5km</td>
<td>Within 4 hours</td>
</tr>
</tbody>
</table>
Urban Atlas

Urban Atlas 2006

Population estimates by Urban Atlas polygon

The Urban Atlas is providing pan-European comparable land use and land cover data for Functional Urban Areas (FUA). The Urban Atlas is a joint initiative of the European Commission Directorate-General for Regional and Urban Policy and the Directorate-General for Enterprise and Industry with the support of the European Space Agency and the European Environment Agency.

Urban Atlas 2006:

- FUAs with more than 100,000 inhabitants as defined by the Urban Audit. The GIS data can be downloaded together with a map for each urban area covered and a report with the metadata.

Urban Atlas 2012:

- 697 UA 2012 FUAs including 301 existing UA2006 FUAs and 394 new FUAs
- Most EU28 cities over 50,000 inhabitants
- 17 urban classes with MMU 0.25 ha; minor nomenclature changes
- 10 Rural Classes with MMU 1ha
- Street Tree Layer (STL) within Urban Areas for selected FUAs (depending on availability of suitable satellite imageries)

Read more (http://land.copernicus.eu/user-corner/technical-library/copy3_of_technical-library#local)
UrbanSIS provides city specific climate data and impact indicators in support to the infrastructure and health sectors operating in cities.

The impact of climate change influenced hazards are considered to be of particular concern for urban infrastructure (buildings, transport systems, sewage and drainage systems) exposed to intense rainfall and river flooding as well as for heat waves and air pollution affecting citizen’s health.

The objective of Urban SIS (Sectoral Information System) is to develop, demonstrate and put into production a method to downscale climate and impact indicators to the urban scale (~1x1km²), delivering the information in such format that it is directly useful for consultants and urban engineers/scientists as input to specific/local models or dimensional calculations concerning in particular the following urban hazards:

- Intense rainfall
- Heat waves
- Extreme air pollution levels

Targets:
- Major European cities

Pilot demonstrations:
- Bologna
- Stockholm
- Amsterdam-Rotterdam

Sectors:
- Infrastructure
- Health
Product Level-2 LST: 1 km LST values and their estimated total uncertainties

Sentinel-3 Pre-Operations Data Hub

https://scihub.copernicus.eu/s3/#/home
GCU’s Test sites:

In the framework of the Working Group of Calibration and Validation (WGCV), the GCU has managed the setting-up of experimental sites in Spain for the calibration of thermal infrared sensors and the validation of Land Surface Temperature (LST) products derived from stations data.
Efecto Isla de Calor Urbana (ICU) en Sevilla
17 Agosto 2018

Imagen diurna. 10:27 UTC

Imagen nocturna. 21:44 UTC

<table>
<thead>
<tr>
<th>Punto</th>
<th>Tipo</th>
<th>Coordenadas</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Urban</td>
<td>37.40246 N, 5.97959 W</td>
</tr>
<tr>
<td>2</td>
<td>Rural</td>
<td>37.44347 N, 6.28261 W</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>T día (°C)</th>
<th>T noche (°C)</th>
<th>Dif (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Urban</td>
<td>43</td>
<td>31</td>
<td>12</td>
</tr>
<tr>
<td>Rural</td>
<td>52</td>
<td>27</td>
<td>25</td>
</tr>
<tr>
<td>SUHI</td>
<td>-9</td>
<td>+4</td>
<td>-13</td>
</tr>
</tbody>
</table>
Efecto Isla de Calor Urbana (ICU) en Sevilla
17 Agosto 2018

Imagen nocturna. 21:44 UTC
RECOMMENDATIONS FOR A FUTURE TIR MISSION

1.- Band configuration

THERMAL INFRARED
Multiespectral: to estimate LSE
TIR (2 in 8-9 microns 2 in 10-12 microns).

VNIR-SWIR-MIR
For atmospheric correction and clasificación

2.- Spatial resolution
UHI (1 km)
UHI – Urban planning: 50 m

3.- Temporal Frequency
daily

4.- Time
Tair near Ts
Between 0 and 6h UTC
We can observe that there is a loss of information beyond 100 m resolution, which makes difficult to capture the urban temperature variations.
**LST-Tair**

**Surface - Air Temperature Difference**

- UAM
- Fireman
- CSIC
- Urbanism
- Printing

**Mean Surface - Air Temperature Differences for all masts**

**Correlation coef. vs. Time**

**Error vs. Time**

- Fireman
- CSIC
- UAM
- Urbanism
- Printing

**Mean Surface - Air Temperature Differences for all masts**

**Surface - Air Temperature Difference**

**Error vs. Time**

**Correlation coef. vs. Time**
LSTM mission

Land Surface Temperature Monitoring (LSTM) mission, in the frame of the expansion of the Copernicus Program led by the European Space Agency (ESA) on behalf of the European Commission.
CONCLUSIONS

• DESIREX 2008 (AHS): UHI=4 K, SUHI=5K.

• SUHI (MODIS): 3 K

• SUHI from COPERNICUS (Sentinel 3)

• Future: ¿SENTINEL 8? 50 m x 50 m
How to mitigate the heat island effect?

- Increase green areas
- Increase albedo
- Reduce building density
- Integrating water
- Maintain / promote ventilation brokers

reduced energy consumption
THANKS FOR YOUR ATTENTION