ASSESSING THE THERMAL ENVIRONMENT IN URBAN AREAS

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Part I: Urban climate
What is the urban climate?

“Urban climate refers to the climatic conditions that prevail in a large metropolitan area which differ from the climate of its surrounding non-urban areas.”
Why dealing with the urban climate?

Urban population is continuously growing worldwide (because of increase in overall population and also because of increasing land use)…

Some facts

- Globally, between 1990 and 2025, the number of people who will live in urban areas is expected to double to more than 5 billion people; about 90% of this growth will occur in the developing world. This means simply, that there is a current addition of 60 million of urban citizens a year, and as mentioned in, ‘is the equivalent of adding another Paris, Beijing or Cairo every other month.

- The population living in urban areas will increase by more than 5% in the following 15 years. By the end of 2015, the world will have 27 mega-cities of which 17 will be in Asia.

- Urban settlements are increasing steadily in all continents, with cities continuing to sprawl, causing environmental stresses.
Why dealing with the urban climate?

We face an important change of the urban climate.

Ambient temperatures increase.

Heat waves are more frequent.

Hot spells have a longer duration.

Poor design and uncontrolled development of urban areas deteriorate the thermal environment in cities.
Temperature rises in major cities around the world (Murakami)
(Source: Japan Meteorological Agency)
What next?

Source: EEA (2015)
BUDAPEST

Temperature (°C)

2015  2025  2035  2045

Temperature - Red
Rainfall - Blue

MILAN

Temperature (°C)

2015  2025  2035  2045

Temperature - Red
Rainfall - Blue

Source: Univ. of Athens, 2017
BERLIN

Source: Univ. of Athens, 2017

ATHENS

Source: Univ. of Athens, 2017
What's an urban climate system like?

BL – Boundary Layer
PBL – Planetary Boundary Layer
UBL – Urban Boundary Layer
UCL – Urban Canopy Layer

Source: Climatic scales and vertical stratification in urban areas., Oke [1987].
Wind speed in the urban canopy layer

Air temperature increase due to the reduction of wind speed.

Wind speed measurements (m/sec) for a street with H/W > 1
yellow: wind speed at the top of CL; red at the surface

Source: Santamouris (2007)
## Characteristics of the urban climate

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean air temperature</td>
<td>1-3°C warmer (occasionally up to 12°C)</td>
</tr>
<tr>
<td>Evaporation</td>
<td>50% less</td>
</tr>
<tr>
<td>Pollution</td>
<td>10-25% higher concentrations</td>
</tr>
<tr>
<td>Cloudiness</td>
<td>5-10% more</td>
</tr>
<tr>
<td>Solar radiation</td>
<td>5-25% less</td>
</tr>
<tr>
<td>Mean wind speed</td>
<td>20–50% of rural wind speed</td>
</tr>
<tr>
<td>Turbulence</td>
<td>10–50% greater</td>
</tr>
</tbody>
</table>

Presentation: Urban climate characteristics & examples, Erik Johansson, Housing Development & Management 2012
The Cooling Load of Buildings is expected to increase by 120% by 2050 and almost 250% by 2100.

Source: Santamouris, 2011
Part II: The physics of the thermal environment (including UHI)
Surface-atmosphere exchanges of heat, mass and momentum can be expressed through the formula: \( Q^* + Q_F = Q_H + Q_E + \Delta Q_S \)

where

- \( Q^* \) [W/m²] Net all wave (short-wave, i.e. solar, and long-wave, i.e. infrared) radiation
- \( Q_F \) [W/m²] Anthropogenic heat flux
- \( Q_H \) [W/m²] Turbulent sensible heat flux (energy that heats the air)
- \( Q_E \) [W/m²] Turbulent latent heat flux (energy that is used to evaporate water)
- \( \Delta Q_S \) [W/m²] Net storage heat flux associated with heating (if positive) or cooling (if negative) of the considered volume
*The all-wave radiation balance*

The net all wave radiation (solar and sky-surface infrared) can be expressed through the formula:

\[
Q^* = Q_S^* + Q_L^* = (Q_S^{\downarrow} - Q_S^{\uparrow}) + (Q_L^{\downarrow} - Q_L^{\uparrow}) \ [\text{W/m}^2]
\]

where

- \(Q_S^{\downarrow}\) \([\text{W/m}^2]\) Short-wave (⇒ solar) incoming radiation
- \(Q_S^{\uparrow}\) \([\text{W/m}^2]\) Short-wave outgoing radiation
  
  \[Q_S^{\uparrow} = \text{SR}_{urb} \ Q_S^{\downarrow}\]

- \(Q_L^{\downarrow}\) \([\text{W/m}^2]\) Long-wave (⇒ thermal IR) incoming radiation
  
  \[Q_L^{\downarrow} = \varepsilon_{sky} \sigma T_{sky}^4\]

- \(Q_L^{\uparrow}\) \([\text{W/m}^2]\) Long-wave outgoing radiation:
  
  \[Q_L^{\uparrow} = (1 - \varepsilon_{urb}) \ Q_L^{\downarrow} + \varepsilon_{urb} \sigma T_{surf}^4\]
Anthropogenic heat
man-made heat sourced from heat radiation from buildings, vehicles and people

Evolution of mean daily $Q_F$ according to the various sources. The black line represents the sum of the various terms, computed each day, whereas the diamonds are monthly averages.  
Anthropogenic heat can be locally huge
Air conditioners increase of urban air temperature by 2-3°C in a reference urban texture.

Source: Salamanca et al. (2010) Theoretical and Applied Climatology 99: 331–344
How to calculate anthropogenic heat

Estimates of anthropogenic heat discharge can be calculated by totaling the energy consumptions from the power grid network.

An alternative methodology to estimate the urban anthropogenic heat is to first estimate the net radiation (Rn), the sensible heat flux (H), the latent heat flux (LE), and the ground heat flux (G) using satellite images coupled with meteorology data and DEM.

\[ R_n + A = G + LE + H \]

G is the ground heat flux: the radiant energy warming/cooling the subsurface of the earth
LE is the latent heat: the heat energy of evaporation
H is the sensible heat: the heat energy transferred between the surface and the air, when there is a difference in temperature between them (by conduction)

The anthropogenic heat discharge is then deemed as the residual of the heat balance equation.
Example of anthropogenic heat flux as deduced from Landsat image

Source: Hong Kong Polytechnic, 2013
Courtesy. National Observatory of Athens
Hot surfaces in the urban fabric

temperature rise [°C]

solar absorptance = 1 - solar reflectance
Source: Cartalis et al., 2016
*Release of turbulent sensible heat*

OK, what's the turbulent sensible heat flux $Q_H$ [W/m²]?

$$Q_H = \rho \ c_p \ w' \ \theta'$$

where

$\rho$ is the air volumic mass, or mass density [kg/m³]

$c_p$ is the air heat capacity [J/(kg K)]

$w'$ expresses the turbulent fluctuations of upward wind velocity [m/s]

$\theta'$ expresses the turbulent fluctuations of temperature [°C]
**Release of turbulent sensible heat**

Maybe easier to read as in Masson (2000) the expression for a generic surface:

\[ Q_H = \rho \ c_p \ (T_{surf} - T_{can}) / RES_{surf} \]

where \( T_{surf} \) and \( T_{can} \) are, respectively, the surface and canyon temperature, and \( RES_{surf} \) the surface aerodynamic resistance.

\[ RES_{surf} = (11.8 + 4.2 \cdot (U_{can}^2 + W_{can}^2)^{1/2})^{-1} \]

where \( U_{can} \) and \( W_{can} \) are the horizontal and vertical wind velocity within the canyon.
Summary of UHI physics

Causes of the UHI:

• High absorption of solar radiation by dark man-made materials deployed in the urban fabric → high surface temperatures of dark materials (up to 50°C higher than the air temperature)

• High release of turbulent sensible heat

• Less vegetated surfaces than in a rural area → less evapotranspiration (+ vegetation presents low surface temperatures, close to air temperature if not lacking of water)

• Low sky view factors → reduced radiative cooling

• Wind velocity reduced by urban roughness → air stagnation & reduced convective cooling

• Anthropogenic heat emissions: in average 40-80 W m⁻² in a typical EU city, but in peak conditions air conditioners may cause an increase up to 2-3°C
Part III. What is an Urban Heat Island?

"An urban heat island (UHI) is the name given to describe the characteristic warmth of both the atmosphere and surfaces in cities (urban areas) compared to their (nonurbanized) surroundings. The heat island is an example of unintentional climate modification when urbanization changes the characteristics of the Earth’s surface and atmosphere."
Cross-section of a typical UHI profile
UHI impacts

Urban Heat Islands

- Thermal discomfort
  - Increase of thermal discomfort especially for sensitive population
  - Increase of extreme temperatures during heat waves

- Energy and economic concern
  - Increase of energy consumption for cooling
  - Increase of peak load for cooling
  - Decrease of AC performance

- Air pollution
  - Increased possibility of smog
  - Increased CO2 emissions
Factors affecting urban heat island intensity

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

- **City Size**
  - linked to form and function

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

- **Synoptic Weather**
  - wind
  - cloud

- **City Form**
  - materials
  - geometry
  - greenspace

**Time**
- day
- season

**Mitigation Measures**
Urban heat islands: Three main types

- Urban Boundary Layer (UBL) Heat Island
- Urban Canopy Layer (UCL) Heat Island
- Surface Urban Heat Island (SUHI)
Heat island intensity
= the measure of the strength or magnitude of the heat island

\[ \text{UHII} = T_{\text{air,urban}} - T_{\text{air,rural}} \]

- max UHI intensity: 3 to 5 h after sunset
- At night hours, urban atmosphere warmer than rural atmosphere
- weak UHI intensity after sunrise or even negative at midday

Heat Island is a very well documented phenomenon in Europe present in almost all latitudes.

The intensity of the phenomenon is quite high exceeding 6-7 Degrees.

New studies performed the very recent period show that in most areas heat island is intensified.
Surface UHI (SUHI)
Cairo (left) - Rome (right)

Source: Chrysoulakis, 2015
SUHI
Madrid (left) – Barcelona (right)

Source: Chrysoulakis, 2015
IMPORTANT

Do not interpret changes in land surface temperature or the urban heat island, before assessing the urban expansion and the corresponding land cover over time and space.
UHI dependence on urban population

![Graph showing the relationship between maximum urban heat island (°C) and population (10^3 to 10^7)]
UHI dependence on urban population density

Source: Spencer: Global Urban Heat Island Effect Study – An Update
The relationship between urban land area and URI.

On the average the cooling load of typical urban buildings is by 13% higher compared to similar buildings in rural areas, with an increase of cooling load of roughly 20% per each °C more of urban heat island intensity.

http://dx.doi.org/10.1016/j.enbuild.2014.07.022
Air pollution vs Temperature
Increase of daily mortality vs temperature (for Athens)

Source: Santamouris and Cartalis, 2017
Part IV: Satellite Remote Sensing and SUHI
Satellite Sensor

- Spatial resolution
  - what size can we resolve

- Spectral resolution
  - what wavelengths do we use

- Temporal resolution
  - how often do we observe

- Radiometric resolution
  - degree of detail observed
The critical balance between spatial and temporal resolution
The Sentinel series will greatly support studies on the thermal environment of cities, both in terms of S-3 which will provide, at a rate of less than two days, thermal data at 1 km x 1m spatial resolution, as well as through S-2 with the latter supporting detailed definition of land use/land cover.
Part V: Estimating LST
Step 1. Develop a data base for your city

<table>
<thead>
<tr>
<th>Month</th>
<th>Jan</th>
<th>Feb</th>
<th>Mar</th>
<th>Apr</th>
<th>May</th>
<th>Jun</th>
<th>Jul</th>
<th>Aug</th>
<th>Sep</th>
<th>Oct</th>
<th>Nov</th>
<th>Dec</th>
<th>Year</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Record high °C (°F)</strong></td>
<td>14.3</td>
<td>19.8</td>
<td>25.6</td>
<td>33.0</td>
<td>36.3</td>
<td>42.6</td>
<td>41.9</td>
<td>38.3</td>
<td>31.0</td>
<td>23.3</td>
<td>19.5</td>
<td>42.6</td>
<td></td>
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<tr>
<td></td>
<td>(57.7)</td>
<td>(67.6)</td>
<td>(75.9)</td>
<td>(91.4)</td>
<td>(96.0)</td>
<td>(108.7)</td>
<td>(107.4)</td>
<td>(100.9)</td>
<td>(87.8)</td>
<td>(66.4)</td>
<td>(59.2)</td>
<td>(67.1)</td>
<td>(108.7)</td>
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<tr>
<td><strong>Average high °C (°F)</strong></td>
<td>1.8</td>
<td>5.0</td>
<td>11.6</td>
<td>20.3</td>
<td>26.0</td>
<td>30.2</td>
<td>30.9</td>
<td>29.7</td>
<td>28.0</td>
<td>19.1</td>
<td>10.1</td>
<td>3.7</td>
<td>17.9</td>
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<td>(35.2)</td>
<td>(41)</td>
<td>(52.9)</td>
<td>(68.5)</td>
<td>(76.8)</td>
<td>(86.4)</td>
<td>(87.6)</td>
<td>(85.5)</td>
<td>(78.4)</td>
<td>(66.4)</td>
<td>(50.2)</td>
<td>(38.7)</td>
<td>(64.1)</td>
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<tr>
<td><strong>Average low °C (°F)</strong></td>
<td>-8.4</td>
<td>-5.6</td>
<td>0.4</td>
<td>7.9</td>
<td>13.6</td>
<td>18.8</td>
<td>22.0</td>
<td>20.8</td>
<td>14.8</td>
<td>7.9</td>
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<td>-5.8</td>
<td>7.2</td>
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<td></td>
<td>(18.9)</td>
<td>(21.9)</td>
<td>(32.7)</td>
<td>(46.2)</td>
<td>(56.5)</td>
<td>(65.8)</td>
<td>(71.6)</td>
<td>(69.4)</td>
<td>(58.8)</td>
<td>(46.2)</td>
<td>(32)</td>
<td>(21.8)</td>
<td>(45.0)</td>
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<tr>
<td><strong>Record low °C (°F)</strong></td>
<td>-18.3</td>
<td>-27.4</td>
<td>-15</td>
<td>-3.2</td>
<td>2.5</td>
<td>8.8</td>
<td>15.3</td>
<td>11.4</td>
<td>3.7</td>
<td>-3.5</td>
<td>-12.5</td>
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<tr>
<td></td>
<td>(-0.9)</td>
<td>(-17.3)</td>
<td>(-5)</td>
<td>(26.2)</td>
<td>(36.5)</td>
<td>(48.6)</td>
<td>(59.5)</td>
<td>(52.5)</td>
<td>(38.7)</td>
<td>(25.7)</td>
<td>(5.5)</td>
<td>(-1.3)</td>
<td>(-17.3)</td>
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<tr>
<td><strong>Precipitation mm (inches)</strong></td>
<td>2.7</td>
<td>4.9</td>
<td>8.3</td>
<td>21.2</td>
<td>34.2</td>
<td>78.1</td>
<td>185.2</td>
<td>159.7</td>
<td>45.5</td>
<td>21.8</td>
<td>7.4</td>
<td>2.8</td>
<td>571.8</td>
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<tr>
<td></td>
<td>(0.106)</td>
<td>(0.193)</td>
<td>(0.327)</td>
<td>(0.835)</td>
<td>(1.346)</td>
<td>(3.075)</td>
<td>(7.291)</td>
<td>(6.287)</td>
<td>(1.791)</td>
<td>(0.856)</td>
<td>(0.291)</td>
<td>(0.11)</td>
<td>(22.51)</td>
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<tr>
<td><strong>Avg. precipitation days (≥ 0.1 mm)</strong></td>
<td>1.8</td>
<td>2.3</td>
<td>3.3</td>
<td>4.3</td>
<td>5.8</td>
<td>9.7</td>
<td>13.6</td>
<td>12.0</td>
<td>7.6</td>
<td>5.0</td>
<td>3.5</td>
<td>1.7</td>
<td>70.6</td>
</tr>
<tr>
<td><strong>% humidity</strong></td>
<td>44</td>
<td>44</td>
<td>46</td>
<td>46</td>
<td>53</td>
<td>61</td>
<td>75</td>
<td>77</td>
<td>68</td>
<td>61</td>
<td>57</td>
<td>49</td>
<td>56.8</td>
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<tr>
<td><strong>Mean monthly sunshine hours</strong></td>
<td>194.1</td>
<td>194.7</td>
<td>231.8</td>
<td>251.9</td>
<td>283.4</td>
<td>261.4</td>
<td>212.4</td>
<td>220.9</td>
<td>232.1</td>
<td>222.1</td>
<td>185.3</td>
<td>180.7</td>
<td>2670.8</td>
</tr>
<tr>
<td><strong>Percent possible sunshine</strong></td>
<td>65</td>
<td>65</td>
<td>63</td>
<td>64</td>
<td>64</td>
<td>59</td>
<td>47</td>
<td>52</td>
<td>63</td>
<td>64</td>
<td>62</td>
<td>62</td>
<td>60</td>
</tr>
</tbody>
</table>

Source: China Meteorological Administration [1], all-time extreme temperature [2]
Step 2. Define Land cover (and its changes)

Left to right: Land cover, satellite image in the visible, thermal image
Step 3. Choose the appropriate spatial (and temporal) resolution

120m resolution

1.1 km resolution

Source: processing by C. Cartalis
Step 4. Choose the right satellite mission – Merge satellite data

LST

Spatial resolution ($\geq 1$ km)

S3

Spatial resolution ($\leq 120$ m)

(Stathopoulou et al., 2004)

AVHRR

AATSR or MODIS

(TM)

ETM+

ASTER

(Stathopoulou et al., 2009)
Step 5. What time of the day? (the impact of thermal capacity)

22:32 local time  
10:30 local time

Source: processing by C. Cartalis

7th ADVANCED TRAINING COURSE ON LAND REMOTE SENSING
4-9 September 2017 | Szent István University | Gödöllő, Hungary
Step 6. Which period of the year?

Source: The Hong Kong Polytechnic University
Step 6. Which period of the year?

LST averages retrieved from L8 TIRS of each residential district for 32 days between 2013 and 2017 of the Canton Basel-Stadt. The scenes are ordered after the DOY of acquisition.

Step 7. Convert and Retrieve

- Thermal channels DN's
- Conversion to radiance
- Conversion to brightness temperature
  - Atmospheric correction
  - Emissivity correction
- LST retrieval

Overall LST accuracy: ±2 Kelvin
Retrieval of Surface Temperature from Landsat TM images

\[ L = 0.0056322 \times DN + 0.1238 \]

\[ T_b = \frac{K_2}{\ln((K_1 / L) + 1)} \]

where \( T_b \) is the brightness temperature in Kelvin, \( L \) is spectral radiance; \( K_1 \) and \( K_2 \) are the calibration constants in m\( \cdot \)W\( \cdot \)cm\(^{-2}\)\( \cdot \)sr\( \cdot \)\( \mu \)m\(^{-1} \) (\( K_1 = 60.776, \ K_2 = 1260.5 \)).

\[ LST = \frac{T_b}{1 + (\lambda \times T_b / \rho) \ln \varepsilon} \]

\[ \rho = \frac{h \times c}{\sigma} \]

where \( \lambda \) is the wavelength of emitted radiance (\( \lambda = 11.5 \ \mu \)m), \( \sigma \) is the Boltzmann constant (\( 1.38 \times 10^{-23} \) J/K), and \( h \) is the Planck’s constant (\( 6.626 \times 10^{-34} \) Js), \( C \) is the velocity of light (\( 2.998 \times 10^8 \) m/s).
Retrieval of land surface temperature from the Moderate Resolution Imaging Spectroradiometer (MODIS)

MODIS has a 36 spectral band spectrometer; its thermal infrared (TIR) bands are used for LST retrieval. The methodology used for the calculation of the LST maps is based on the Split Window Technique (SWT). Using the SWT, LST is calculated as (Ts), (Jiménez-Muñoz et al., 2008):

$$Ts = Ti + c1 (Ti - Tj) + c2 (Ti - Tj)^2 + c0 + (c3 + c4*W) (1 - \varepsilon) + (c5 + c6*W) \Delta \varepsilon$$

where:

- $Ti$ and $Tj$: at-sensor brightness temperatures at the SW bands $i$ and $j$ (in Kelvin)
- $\varepsilon$: the mean emissivity, $\varepsilon = 0.5(\varepsilon_i + \varepsilon_j)$
- $\Delta \varepsilon$: the emissivity difference, $\Delta \varepsilon = (\varepsilon_i - \varepsilon_j)$
- $W$ is the total atmospheric water vapor content (in grams per square centimeter)
- $c0$–$c6$: the SWT coefficients

In the case of the MODIS sensors $i$ and $j$ are bands 31 and 32, at 10.780–11.280 $\mu$m and 11.770–12.270 $\mu$m respectively.
Retrieval of Land Surface Temperature from AATSR data

Source: Tangtang Zhang et al., 2008
**DOWNSCALING**

One of the techniques to be used in order to improve the spatial resolution of satellite images relates to the use of LSTs or emissivities (PBIM - pixel block intensity modulation, Guo and Moore, 1998; Stathopoulou and Cartalis, 2007):

\[
T_{\text{Sentinel3,30}} = T_{\text{Sentinel3,1000}} \times \frac{T_{\text{landsat,30}}^{27/7/16}}{T_{\text{landsat,30}}^{27/7/16}}
\]

\[
T_{\text{Sentinel3,30}} = T_{\text{Sentinel3,1000}} \times \frac{\varepsilon_{\text{landsat,30}}}{\varepsilon_{\text{landsat,30}}} \times \frac{1000}{1000}
\]

Corrected image high spatial resolution

Initial image of low spatial resolution

Initial value of high spatial resolution (LANDSAT)

Mean LST for an area corresponding to the area of Sentinel – 3 (LANDSAT)

Emissivity for an image of high spatial resolution (LANDSAT)

Mean emissivity for an area corresponding to the area of Sentinel 3
Part VI: UHI Mitigation

Source: Santamouris, 2014; Santamouris and Cartalis, 2015
## UHI mitigation techniques

<table>
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<tr>
<th>Methods</th>
<th>Applications examples</th>
</tr>
</thead>
<tbody>
<tr>
<td>Creation of cool surfaces</td>
<td>Use of appropriate materials</td>
</tr>
<tr>
<td></td>
<td>Green areas</td>
</tr>
<tr>
<td></td>
<td>Water surfaces</td>
</tr>
<tr>
<td></td>
<td>Creation of shading area</td>
</tr>
<tr>
<td>Reduction of anthropogenic heat</td>
<td>Energy conservation measures</td>
</tr>
<tr>
<td></td>
<td>Heat release measures</td>
</tr>
<tr>
<td>Improvement of the urban environment</td>
<td>City block configuration</td>
</tr>
<tr>
<td></td>
<td>Building configuration</td>
</tr>
</tbody>
</table>

- Pavements and roofs comprise over 60% of urban surfaces. Vegetation cover presents a low percentage.
Cool materials

- high solar reflectance
- high infrared emittance

- less solar radiation absorbed
- faster release of heat (IR radiation)

- lower surface T

- less heat penetrates into the building
- less heat transferred to ambient air
Example of urban regeneration project: at the top the thermal environment before the project and below after the use of cool materials (Courtesy: M. Santamouris, Laboratory of Building Physics, Univ. of Athens).
Simulation of roof top temperatures for albedo values: 0.18, 0.63 and 0.85 (left to right). Green to red: from higher to lower temperatures.