ASSESSING THE THERMAL ENVIRONMENT IN URBAN AREAS

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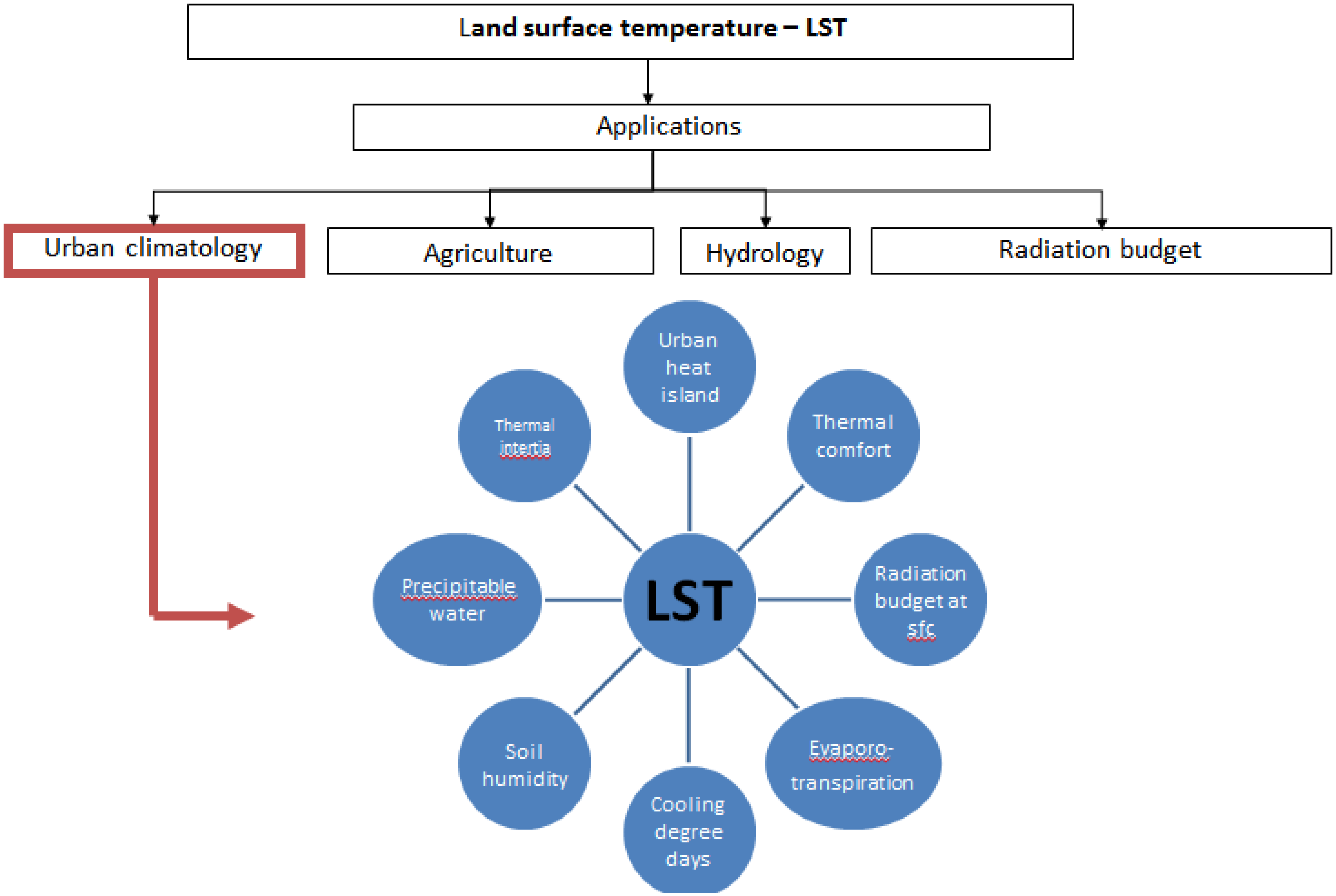
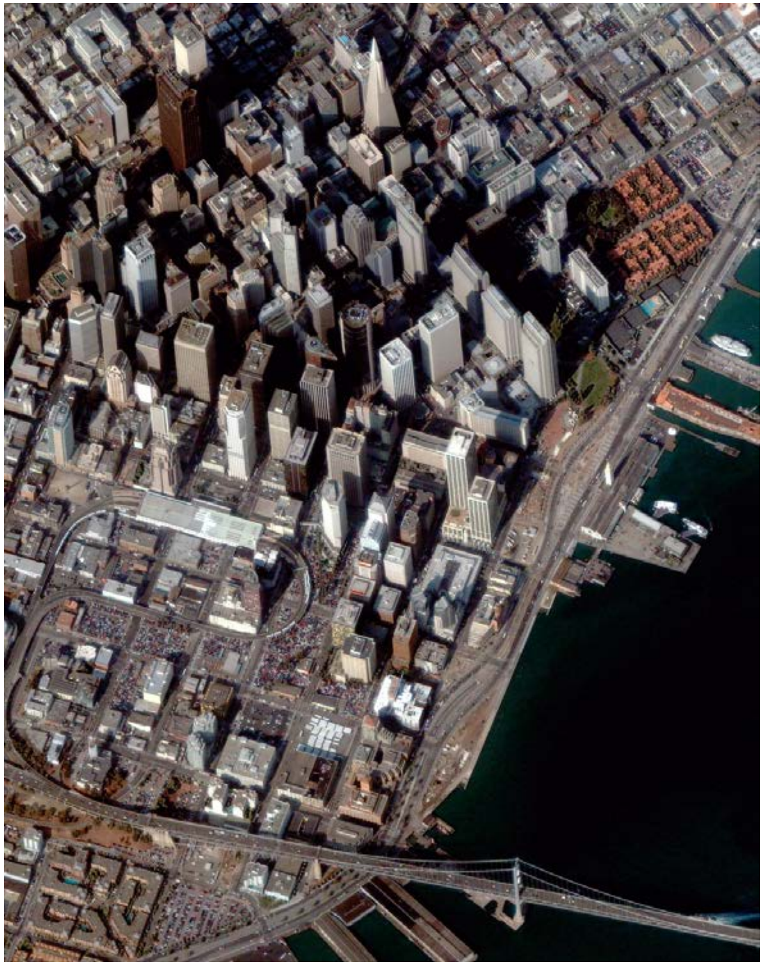

Land surface temperature – LST
Applications
Urban climatology
Agriculture
Hydrology
Radiation budget
Urban heat island
Thermal intertia
Thermal comfort
Precipitable water
LST
Radiation budget at sfc
Soil humidity
Cooling degree days
Evaporo-transpiration

Part I: Urban climate

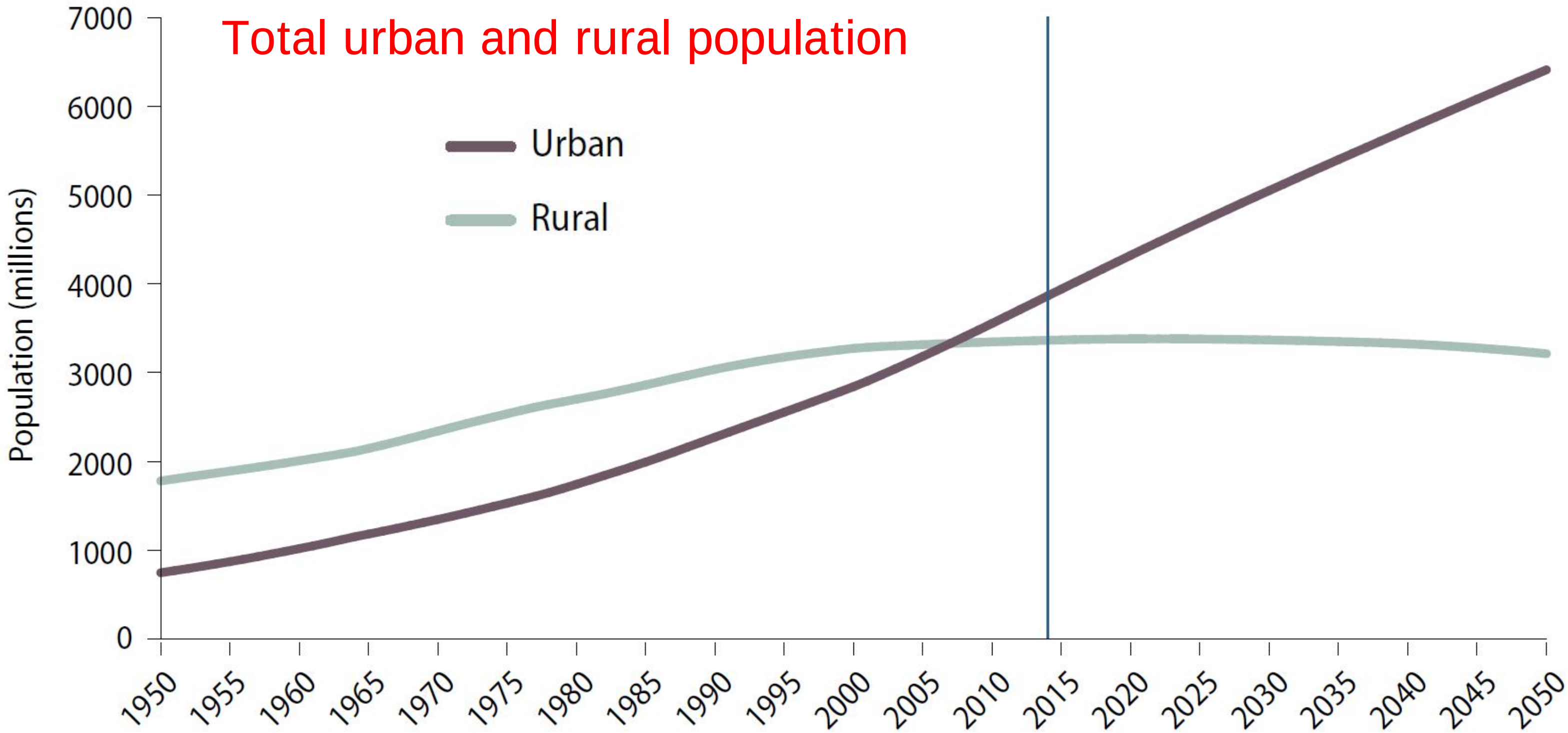
What is the urban climate?



"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)...



Source: UN World Urbanization Prospects. 2014 Revision, http://esa.un.org/Unpd/Wup/

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 <u>60 million of urban citizens a year</u>, 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?

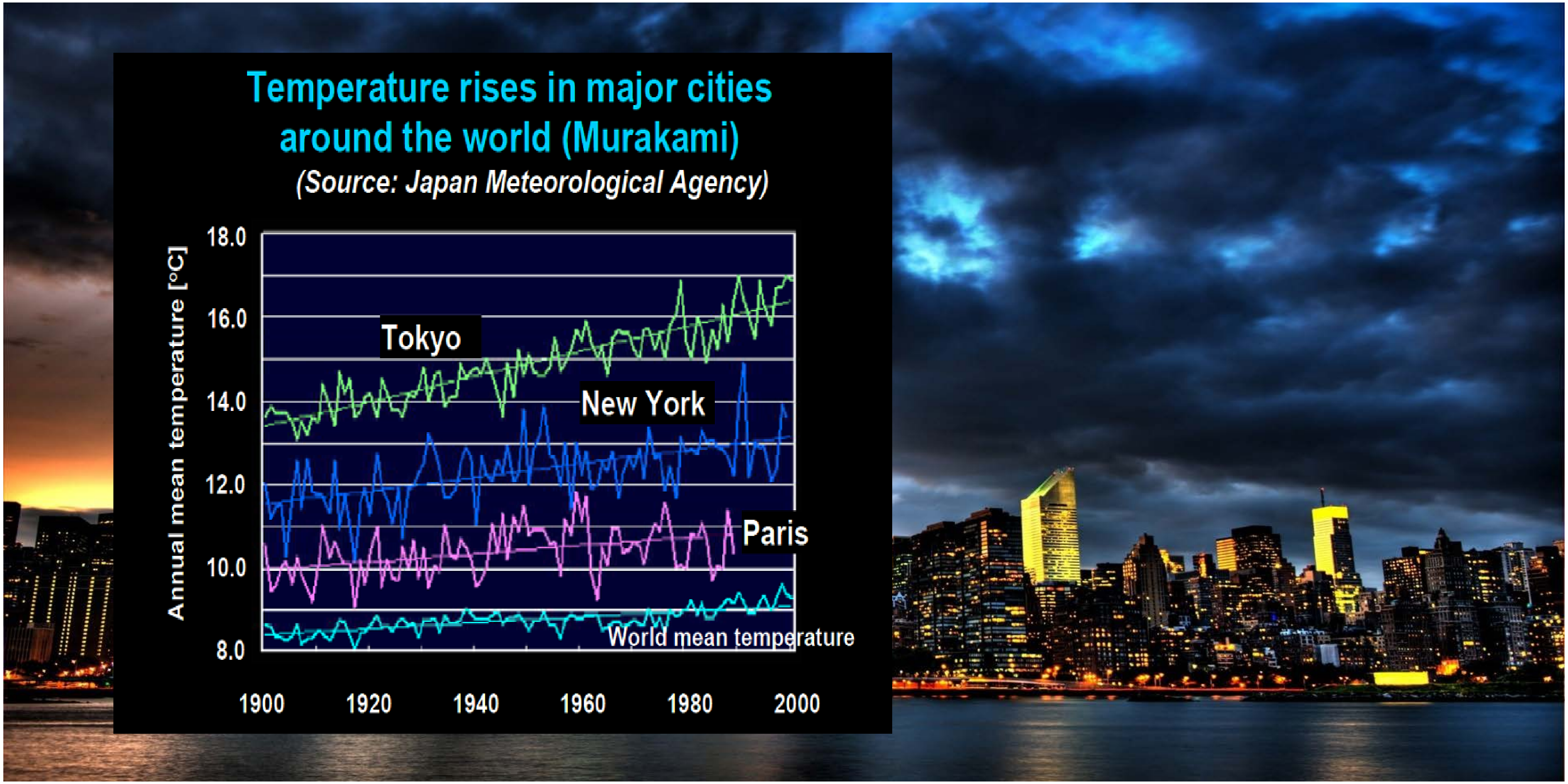
We face an important change of the urban climate.

Ambient temperatures increase.

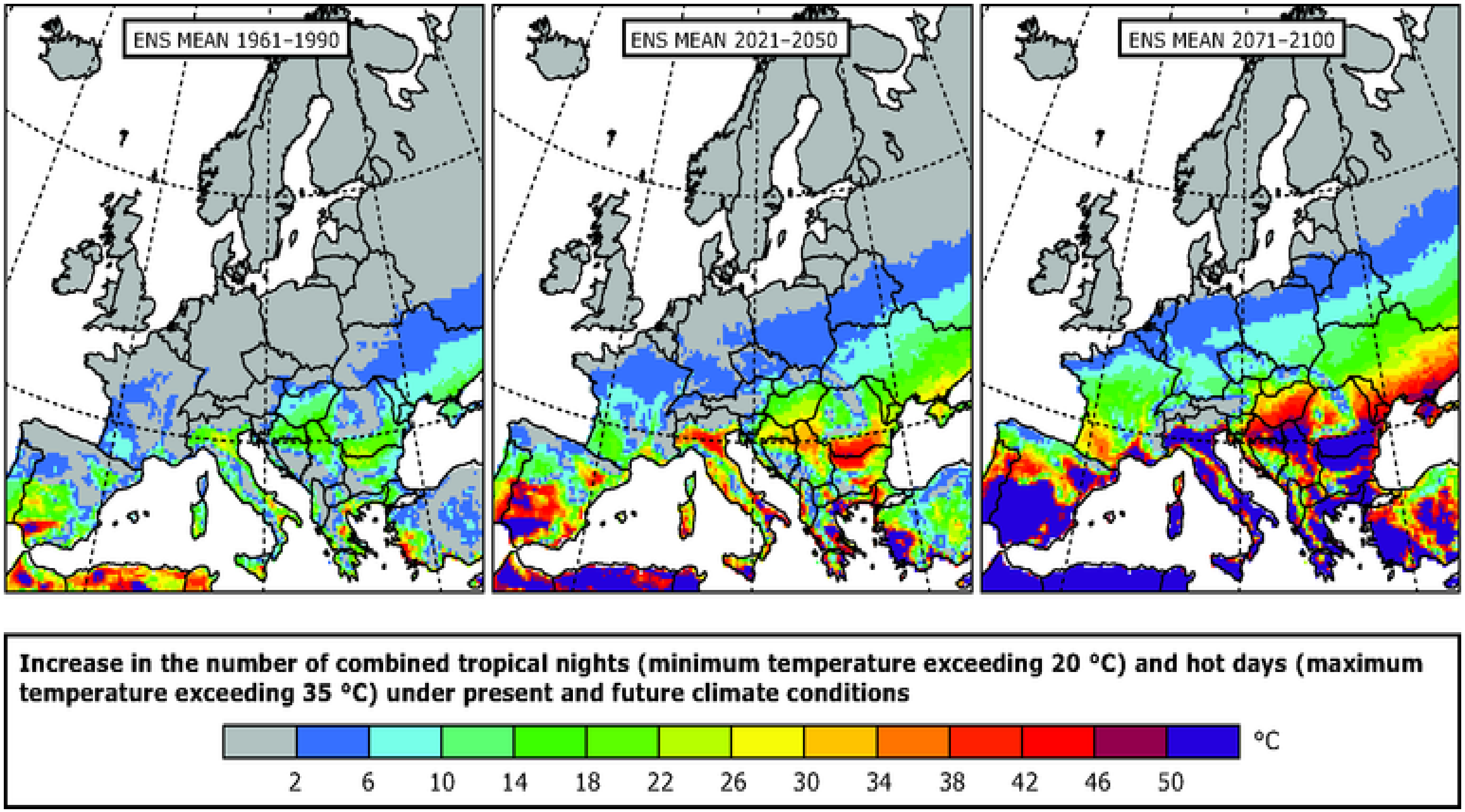
Heat waves are more frequent.

Hot spells have a longer duration.

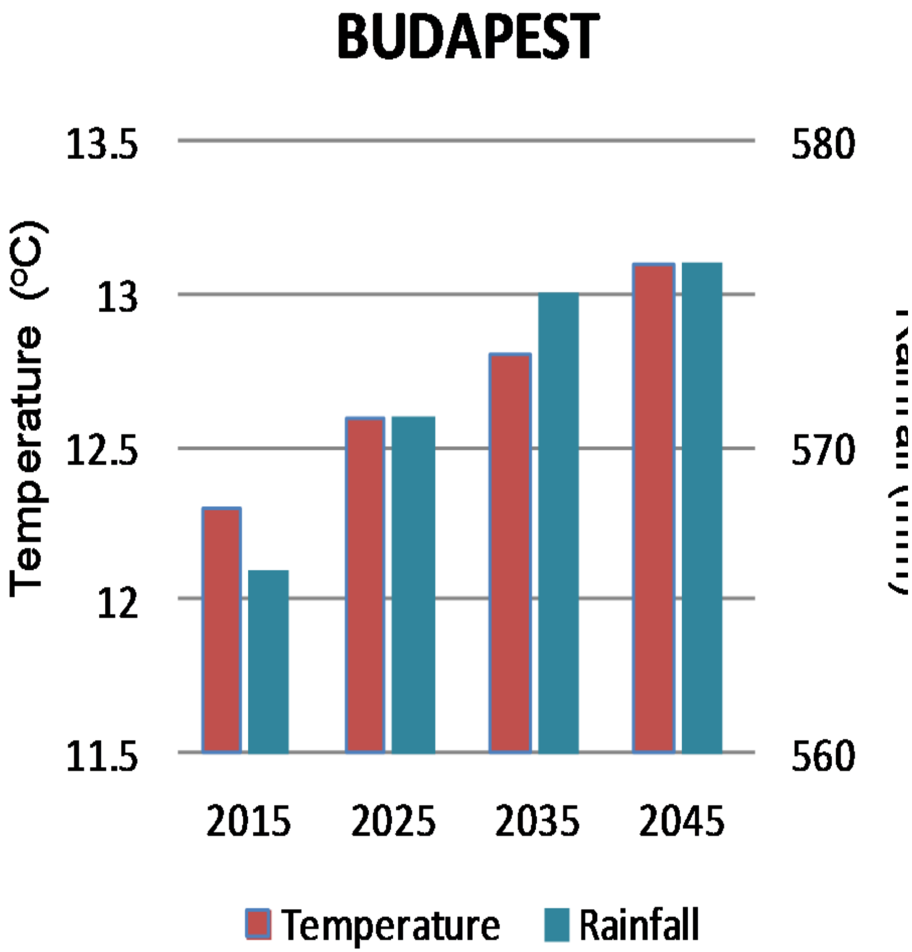
Poor design and uncontrolled development of urban areas deteriorate the thermal environment in cities.

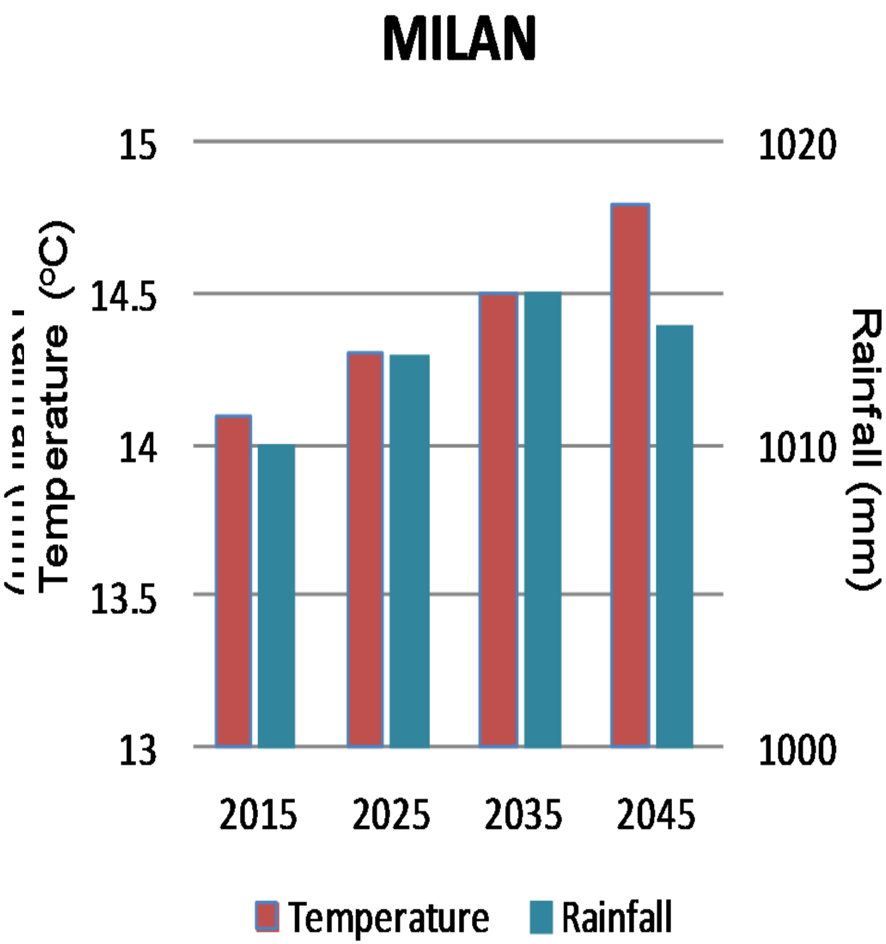

Temperature rises in major cities around the world (Murakami)
(Source: Japan Meteorological Agency)
Annual mean temperature [°C]
18.0
16.0
14.0
12.0
10.0
8.0
Tokyo
New York
Paris
World mean temperature
1900
1920
1940
1960
1980
2000

What next ?

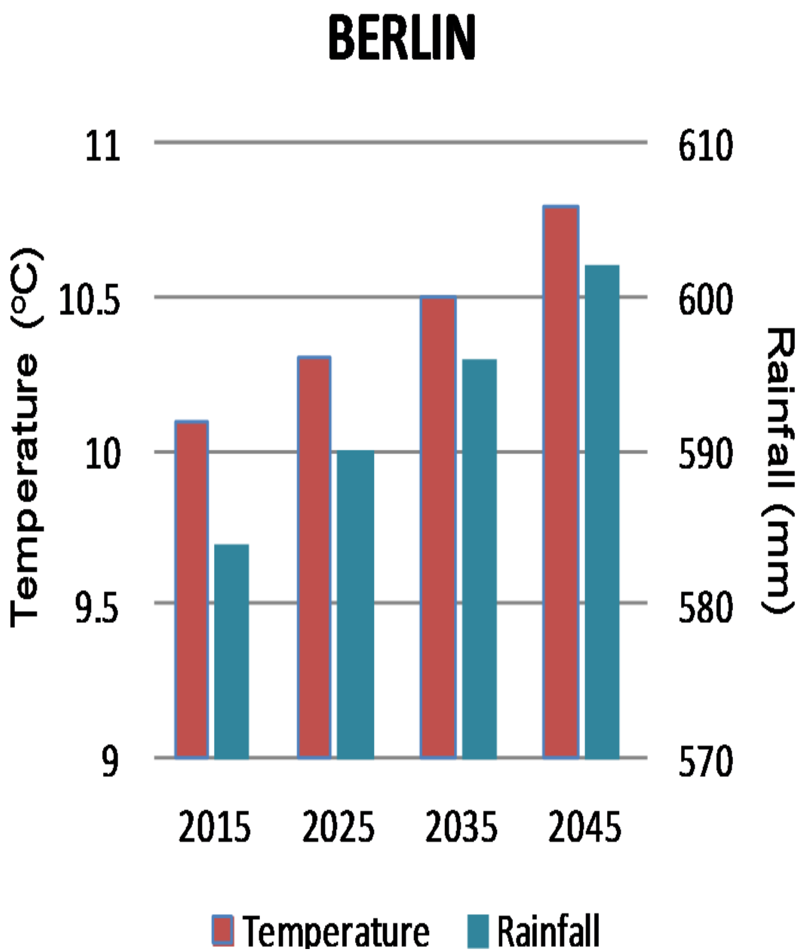


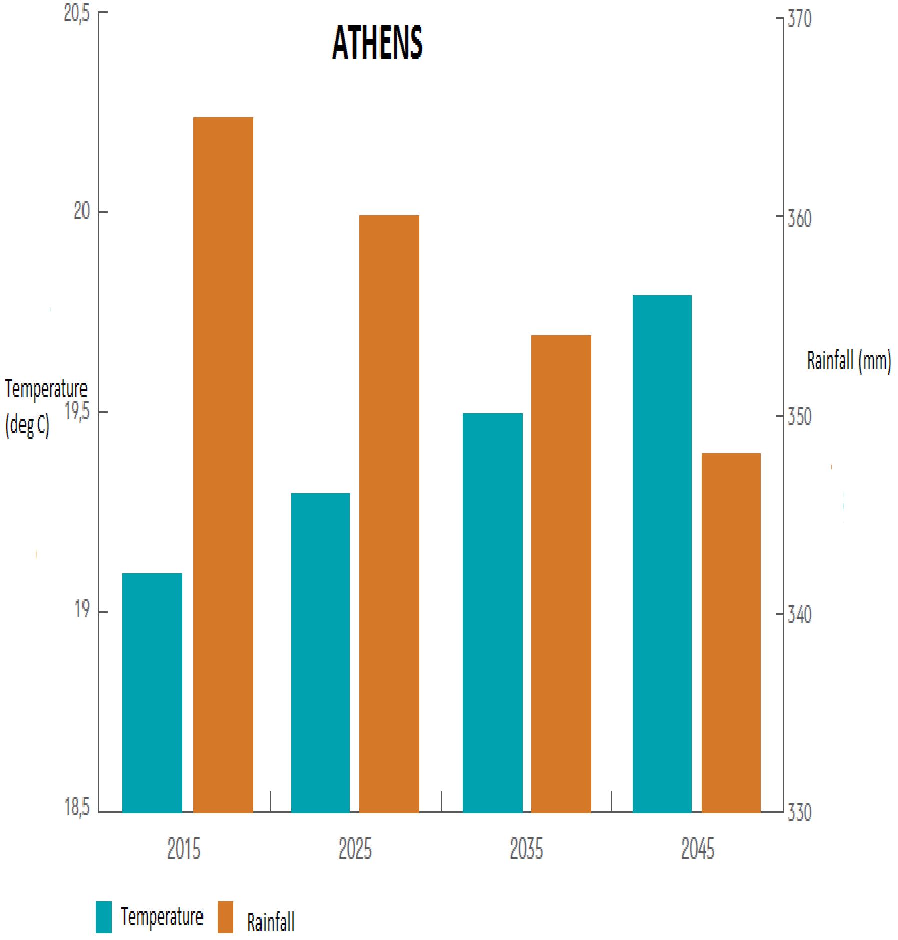
Source: EEA (2015)





Source: Univ. of Athens, 2017

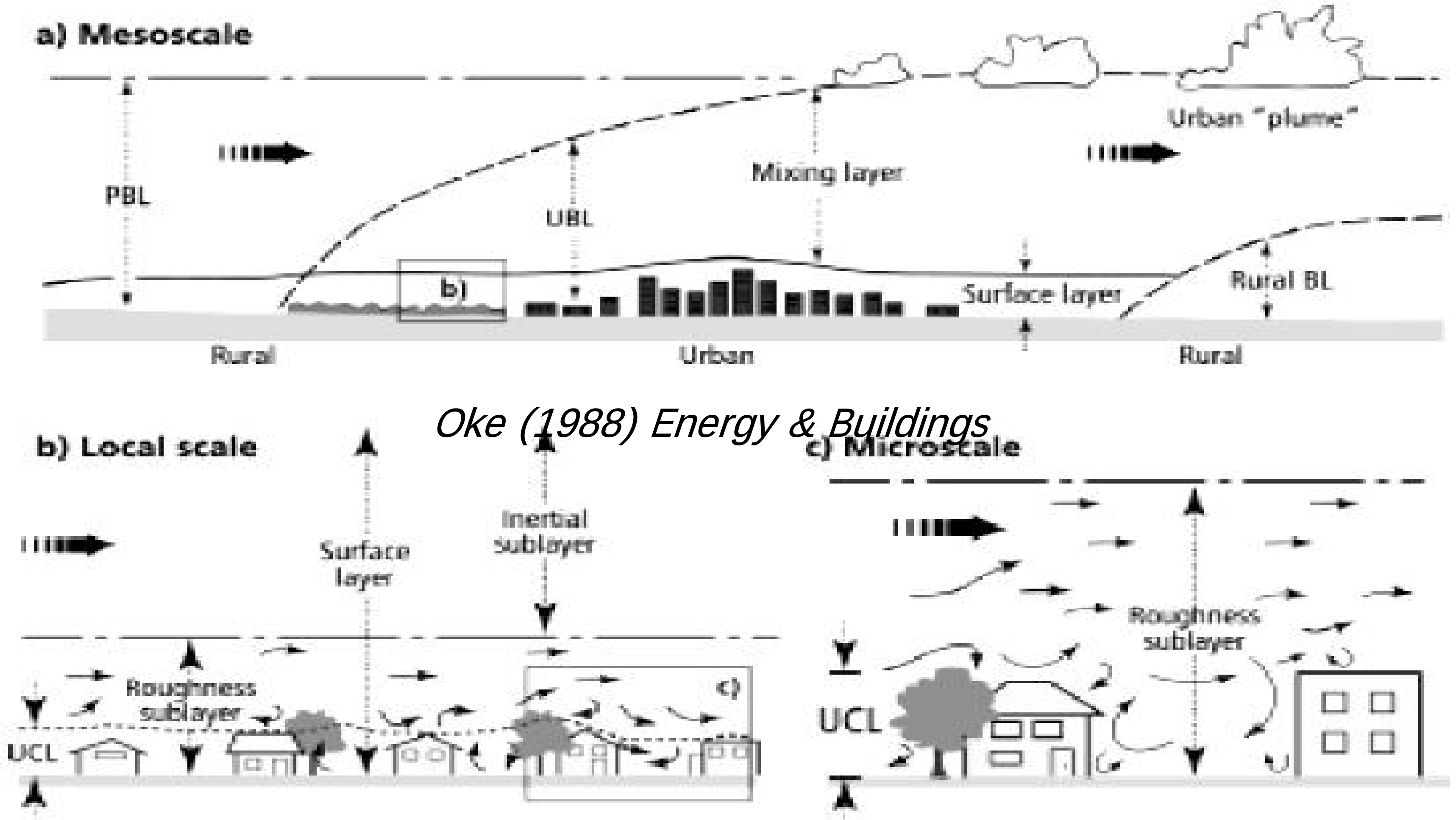




Source: Univ. of Athens, 2017

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

What's an urban climate system like?

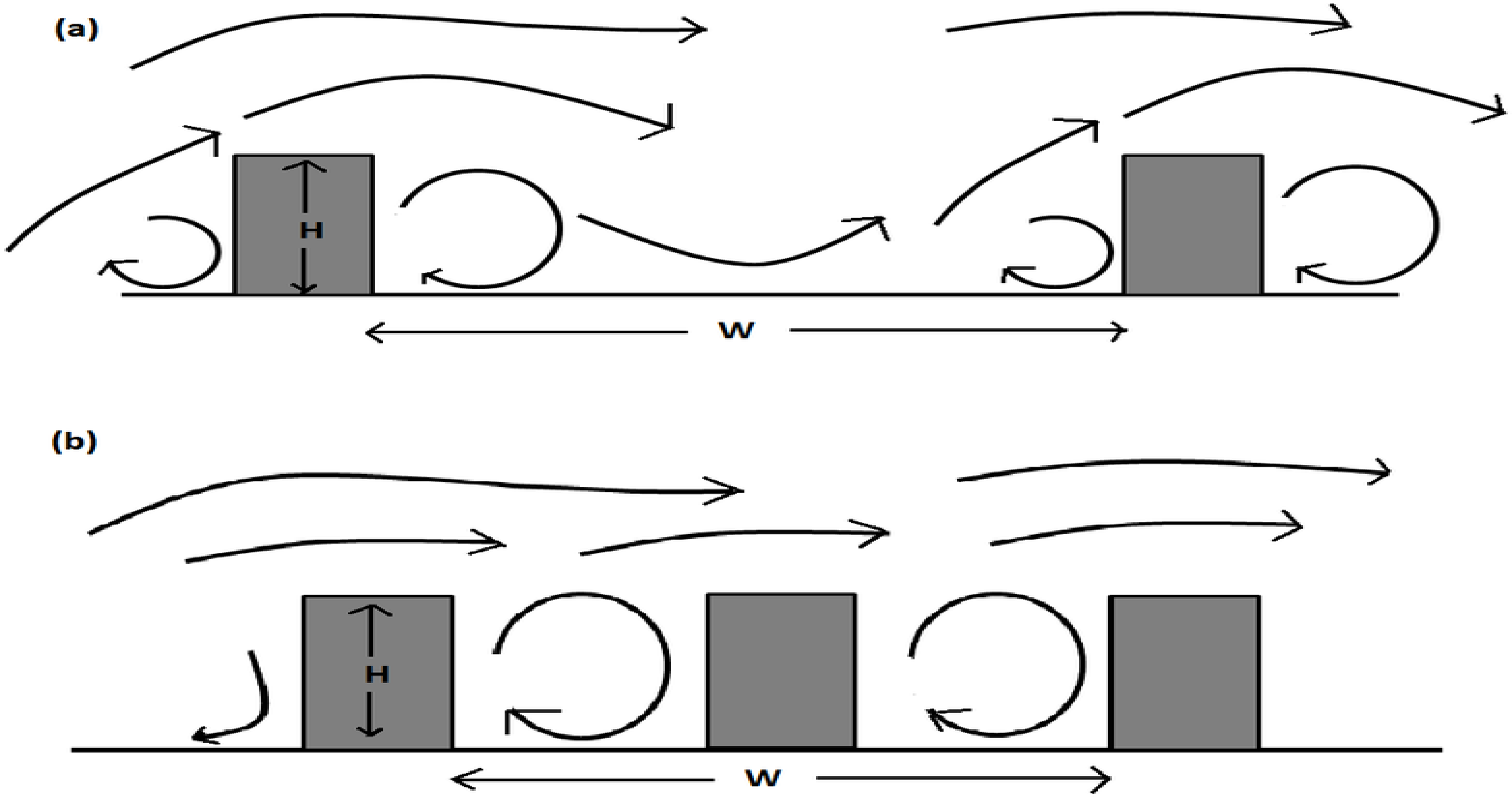


Oke (1988) Energy & Buildings

Source: Climatic scales and vertical stratification in urban areas., Oke [1987].

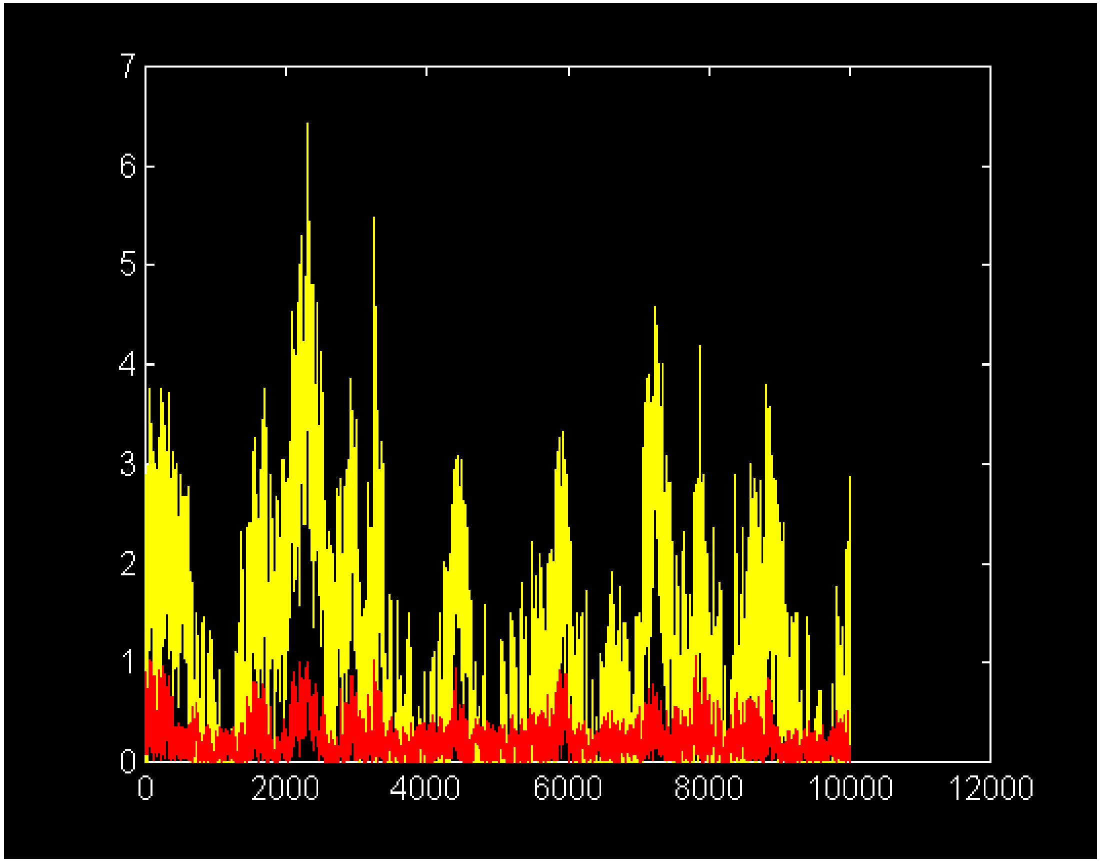
Wind speed in the urban canopy layer

Air temperature increase due to the reduction of wind speed.



Oke (1988) Energy & Buildings

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



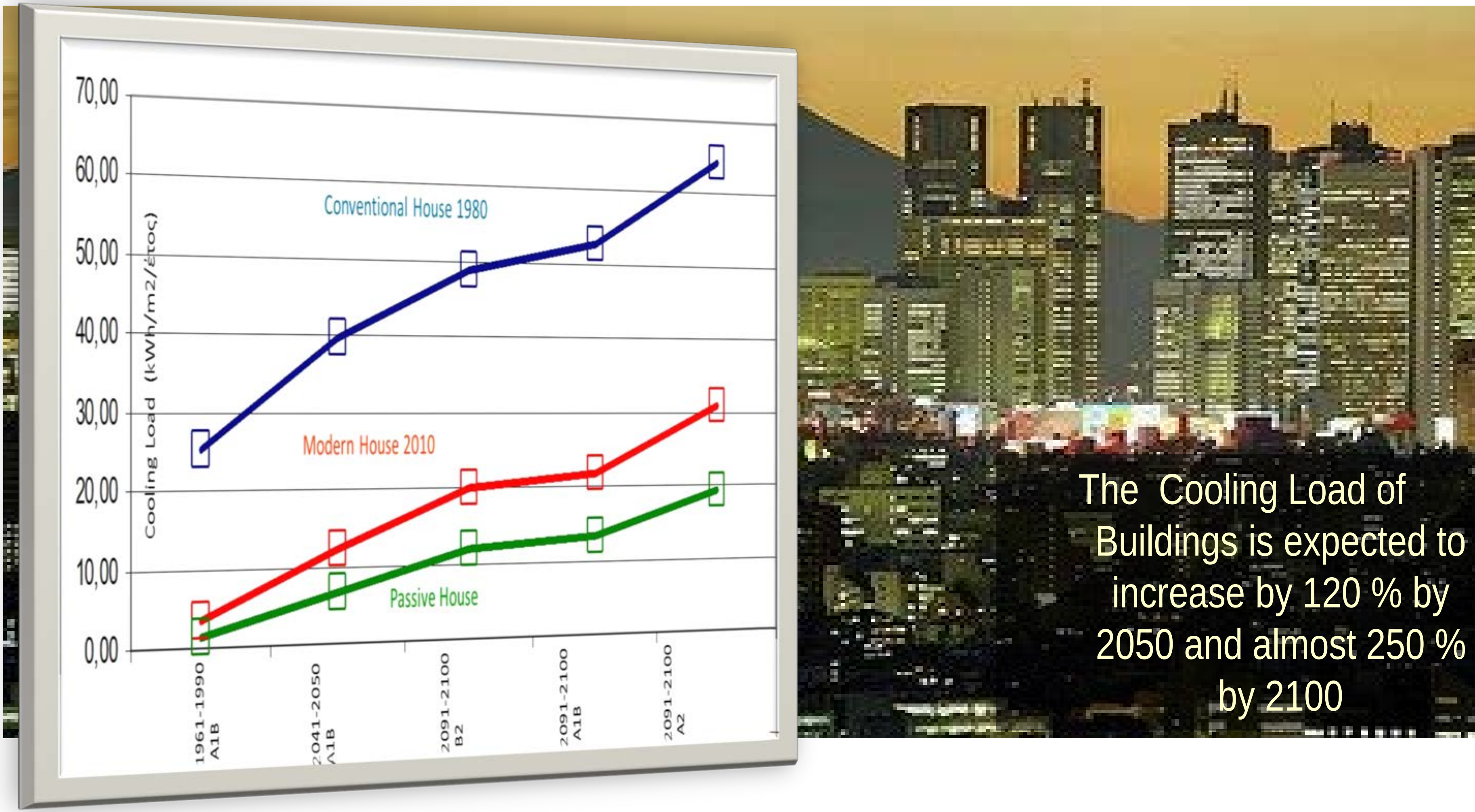
Source: Santamouris (2007)

Characteristics of the urban climate

Mean air temperature:	1-3°C warmer (occasionally up to 12°C)
Evaporation:	50% less
Pollution:	10-25% higher concentrations
Cloudiness:	5-10% more
Solar radiation:	5-25% less
Mean wind speed:	20–50% of rural wind speed
Turbulence:	10–50% greater

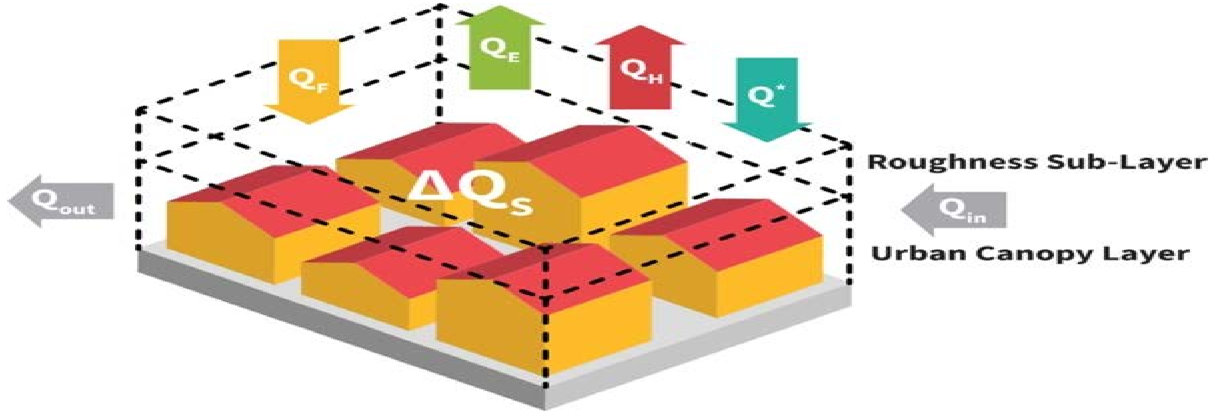
Presentation: Urban climate: characteristics & examples, Erik Johansson Housing Development & Management 2012

IMPACT OF URBAN CLIMATE CHANGE



Source: Santamouris, 2011

Part II: The physics of the thermal environment (including UHI)



*The Urban Surface Energy Balance

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)

ΔQ_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:

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

where

$Q_S\downarrow$ $[W/m^2]$ Short-wave ($\Rightarrow$ solar) incoming radiation

$Q_S\uparrow$ $[W/m^2]$ Short-wave outgoing radiation

$$Q_S\uparrow = SR_{urb}\ Q_S\downarrow$$

$Q_L\downarrow$ $[W/m^2]$ Long-wave ($\Rightarrow$ thermal IR) incoming radiation

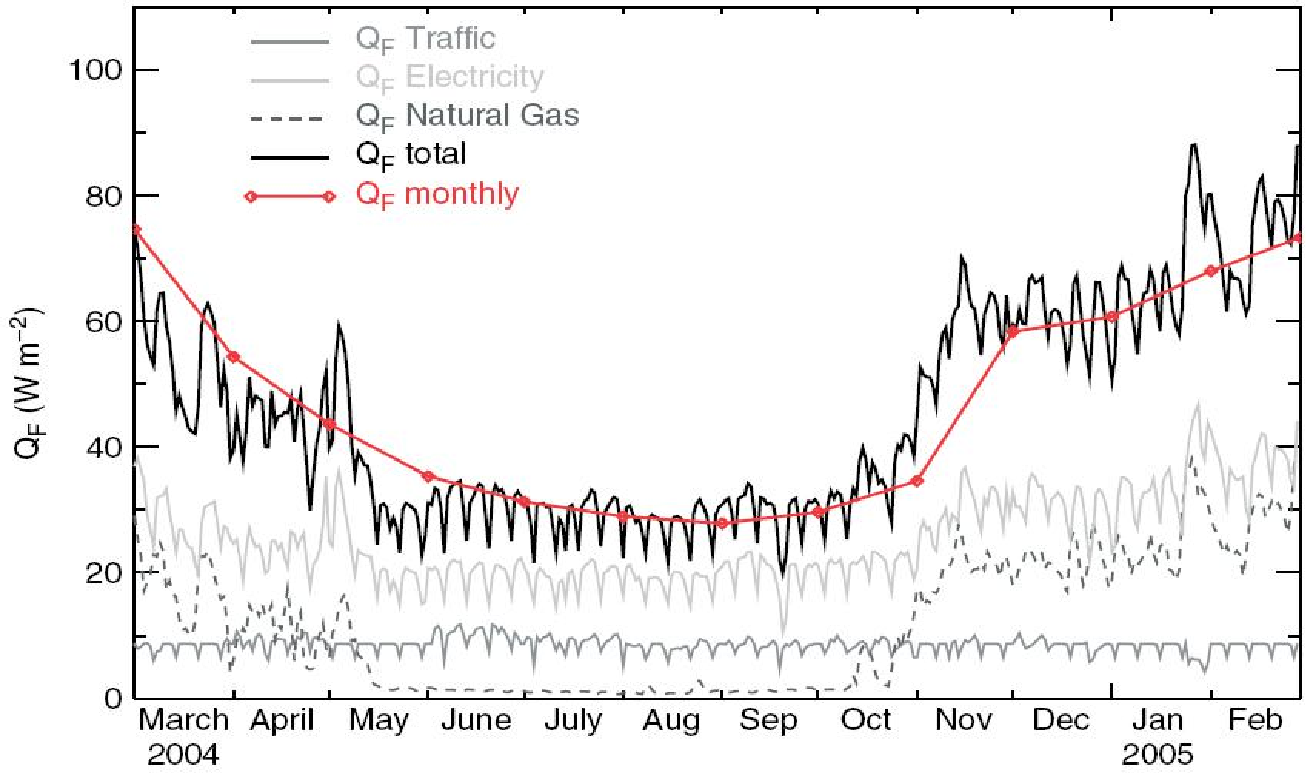
$$Q_L\downarrow = \varepsilon_{sky}\sigma T_{sky}^4$$

$Q_L\uparrow$ $[W/m^2]$ 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. *Source: Pigeon et al (2007)*

Anthropogenic heat can be locally huge

Air conditioners increase of urban air temperature by 2-3°C in a reference urban texture.

Athens, Greece

Source Salamanca et al. (2010) Theoretical and Applied Climatology 99: 331–344

Fuzhou, China

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.

$$R_n + \mathbf{A} = G + LE + H$$

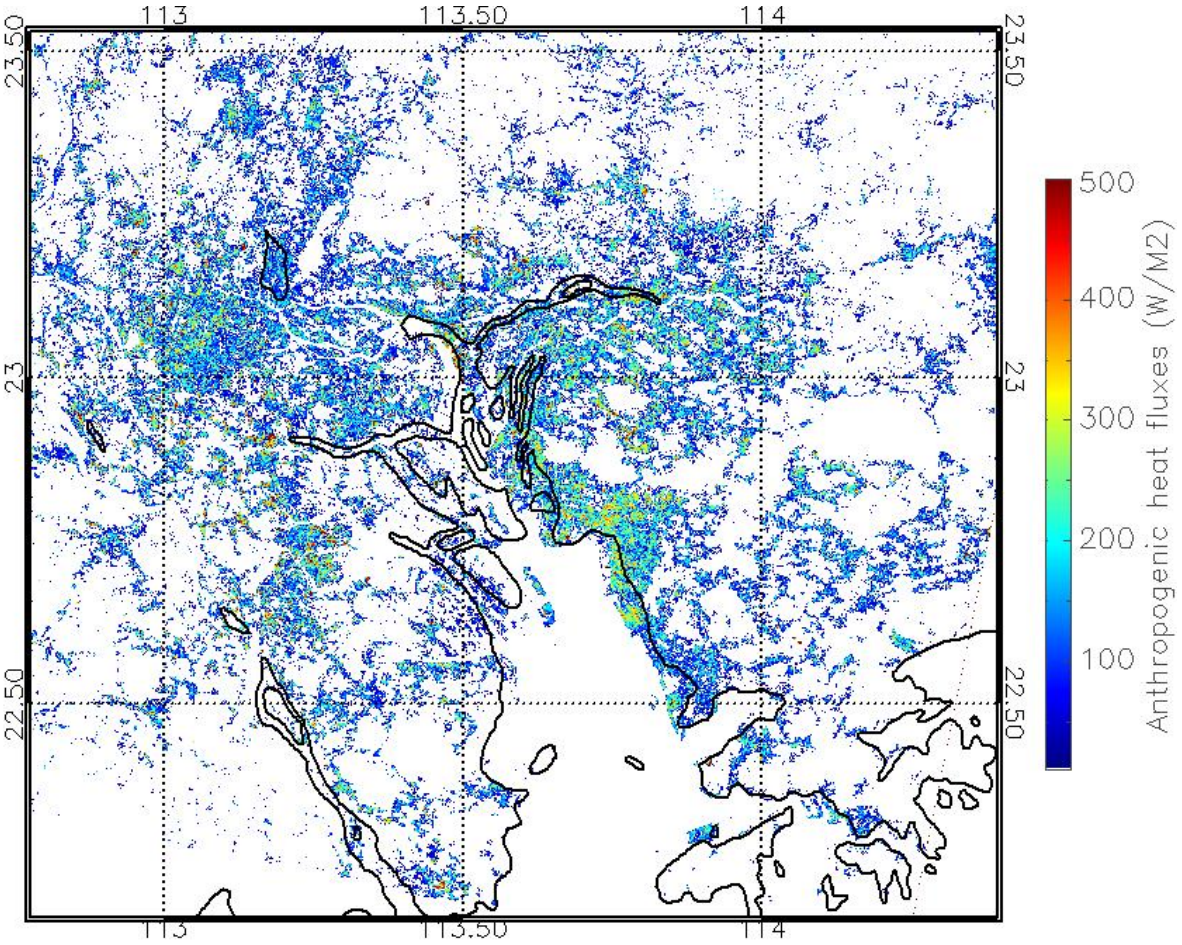
G is the ground heat flux: the radiant energy warming/cooling the subsurface of the earth

LE is the latent heat: the heat energy of evaporation

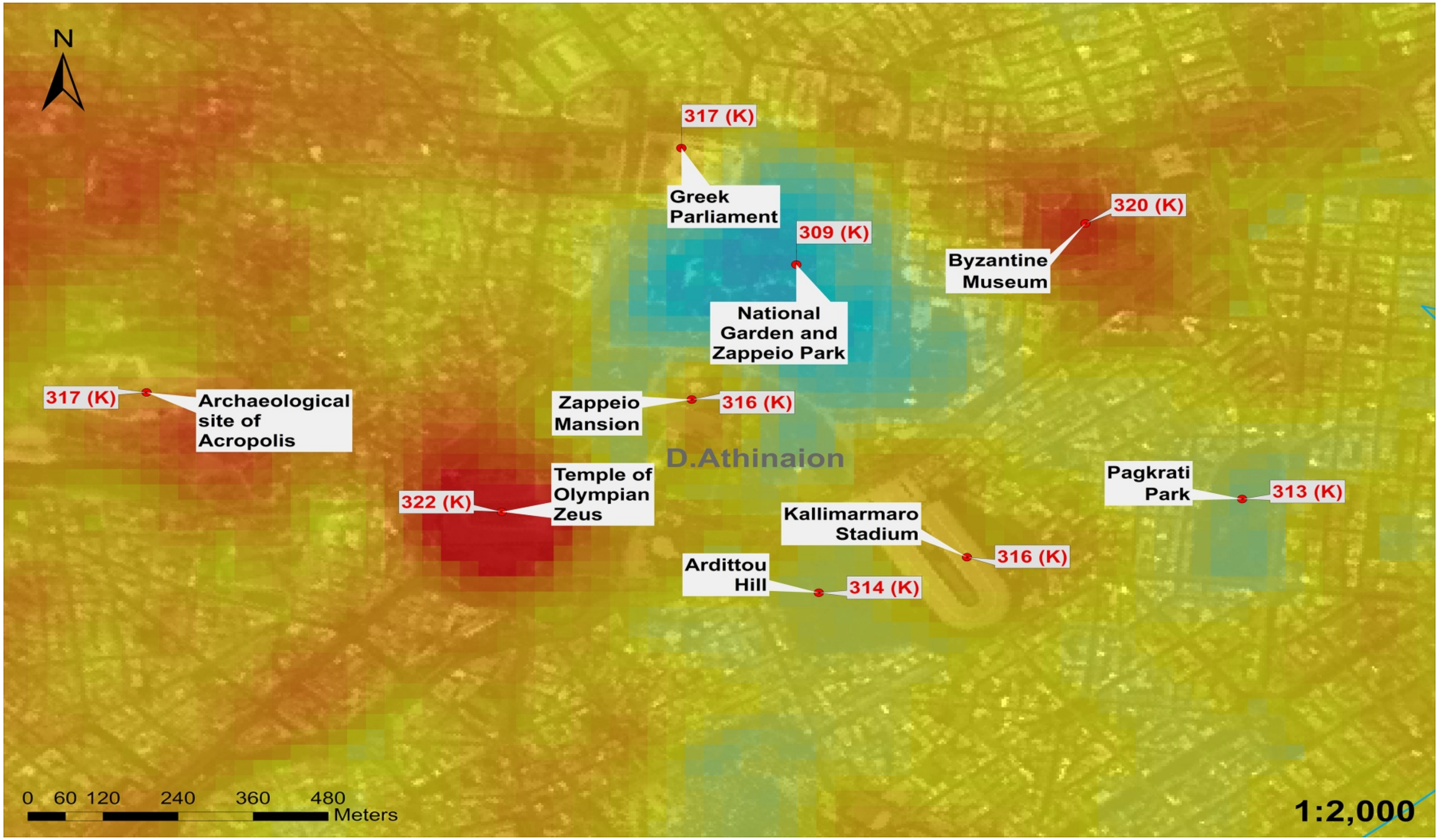
H is the sensible heat: the heat energy transferred between the surface and the air, when there is a difference in temperature between them (by conduction)

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

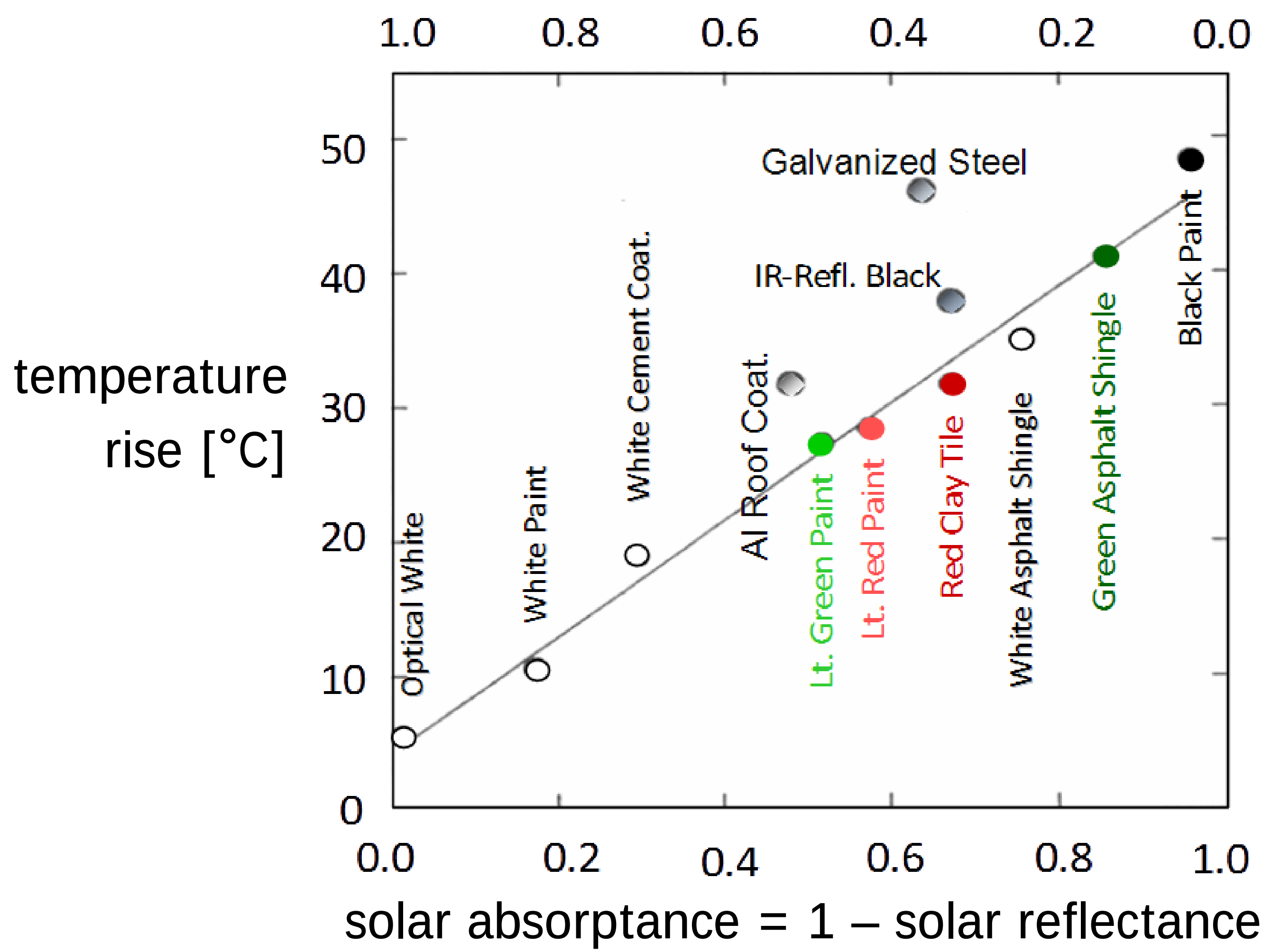


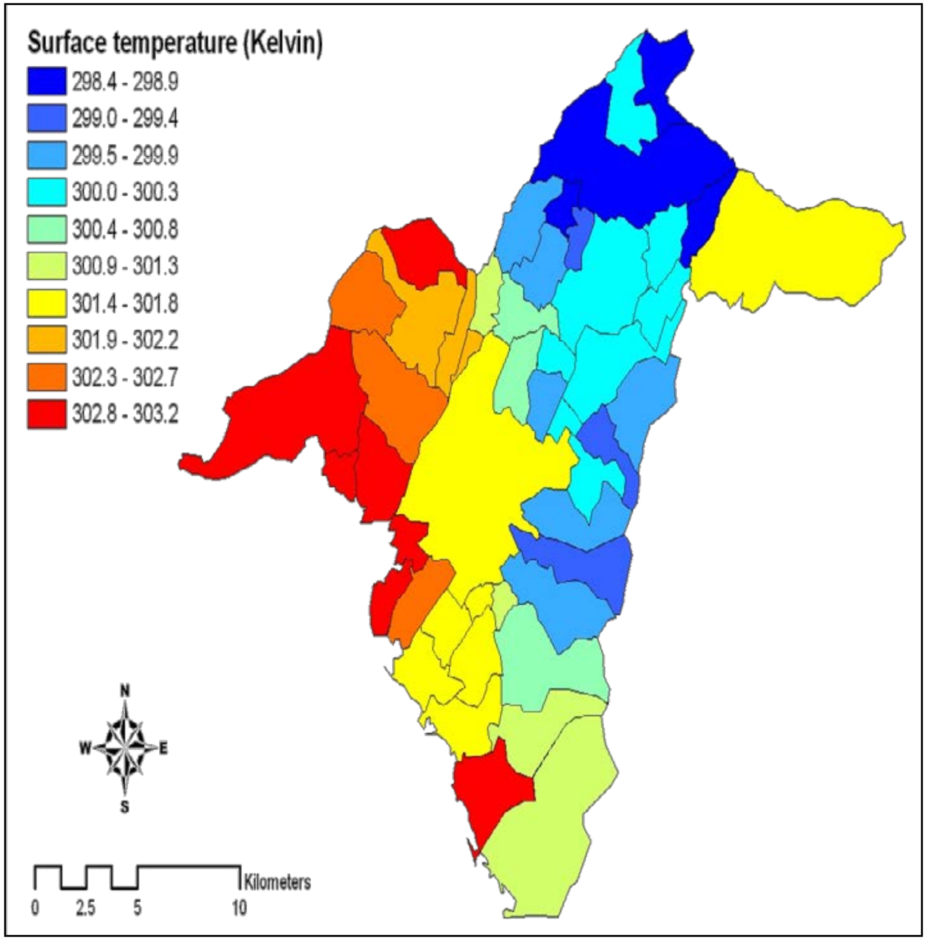
Source: Hong Kong Polytechnic, 2013

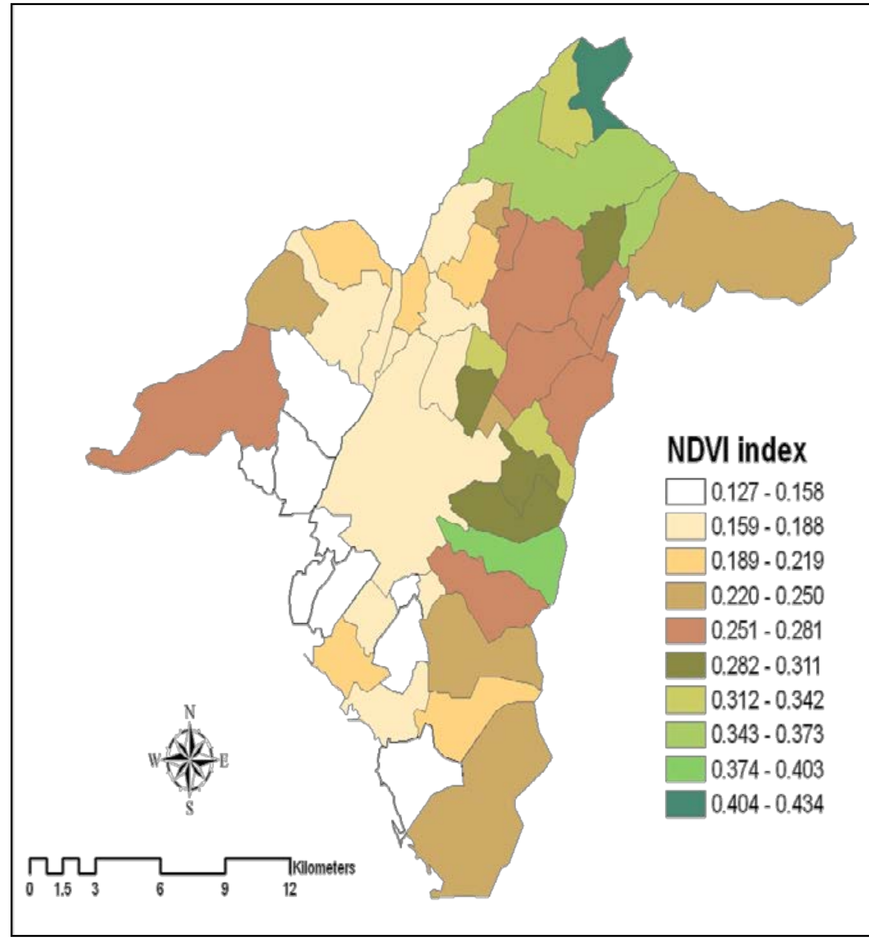


Courtesy. National Observatory of Athens

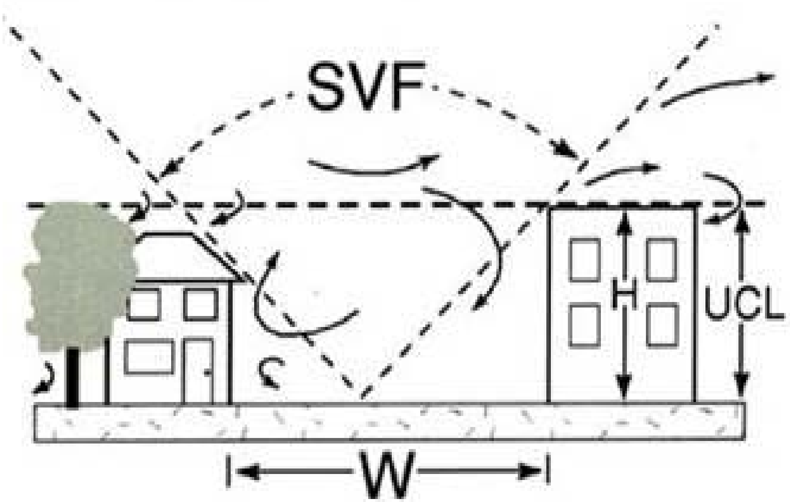
Hot surfaces in the urban fabric

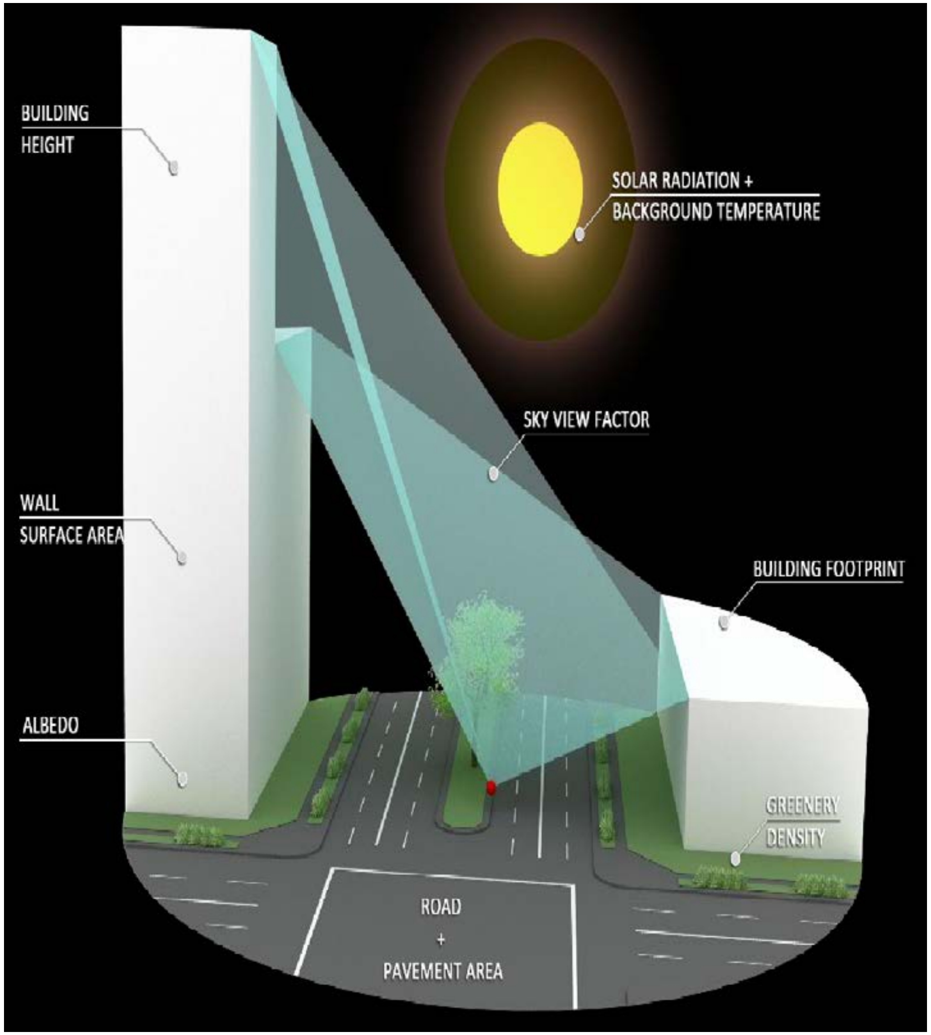


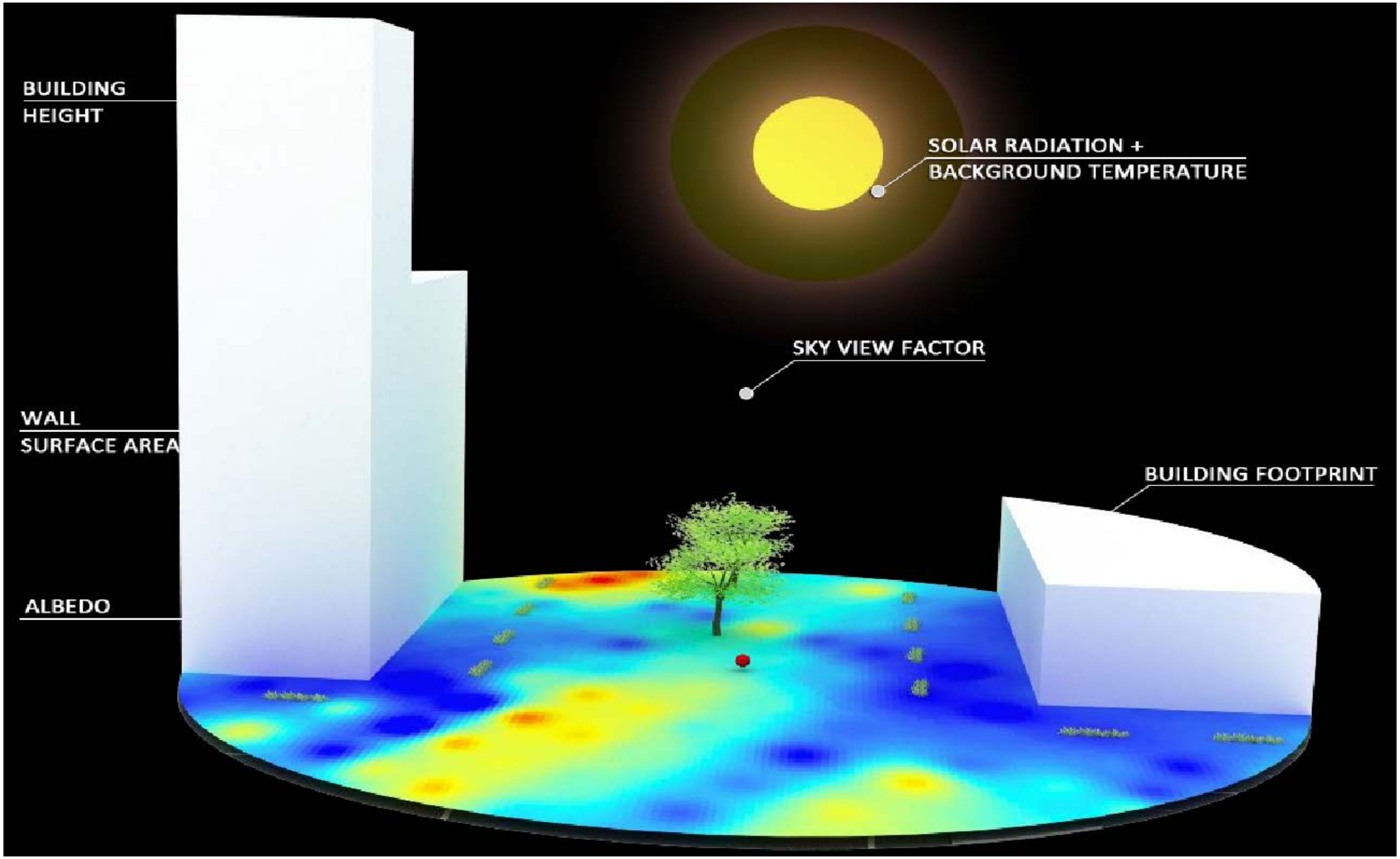




Source: Cartalis et al., 2016


SVF
H
UCL
W


BUILDING HEIGHT
SOLAR RADIATION + BACKGROUND TEMPERATURE
SKY VIEW FACTOR
WALL SURFACE AREA
BUILDING FOOTPRINT
ALBEDO
GREENERY DENSITY
ROAD + PAVEMENT AREA


BUILDING
HEIGHT
SOLAR RADIATION +
BACKGROUND TEMPERATURE
SKY VIEW FACTOR
WALL
SURFACE AREA
BUILDING FOOTPRINT
ALBEDO

*Release of turbulent sensible heat

OK, what's the turbulent sensible heat flux Q_H [W/m^2]?

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

where

ρ is the air volumic mass, or mass density [kg/m^3]

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

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

θ' 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

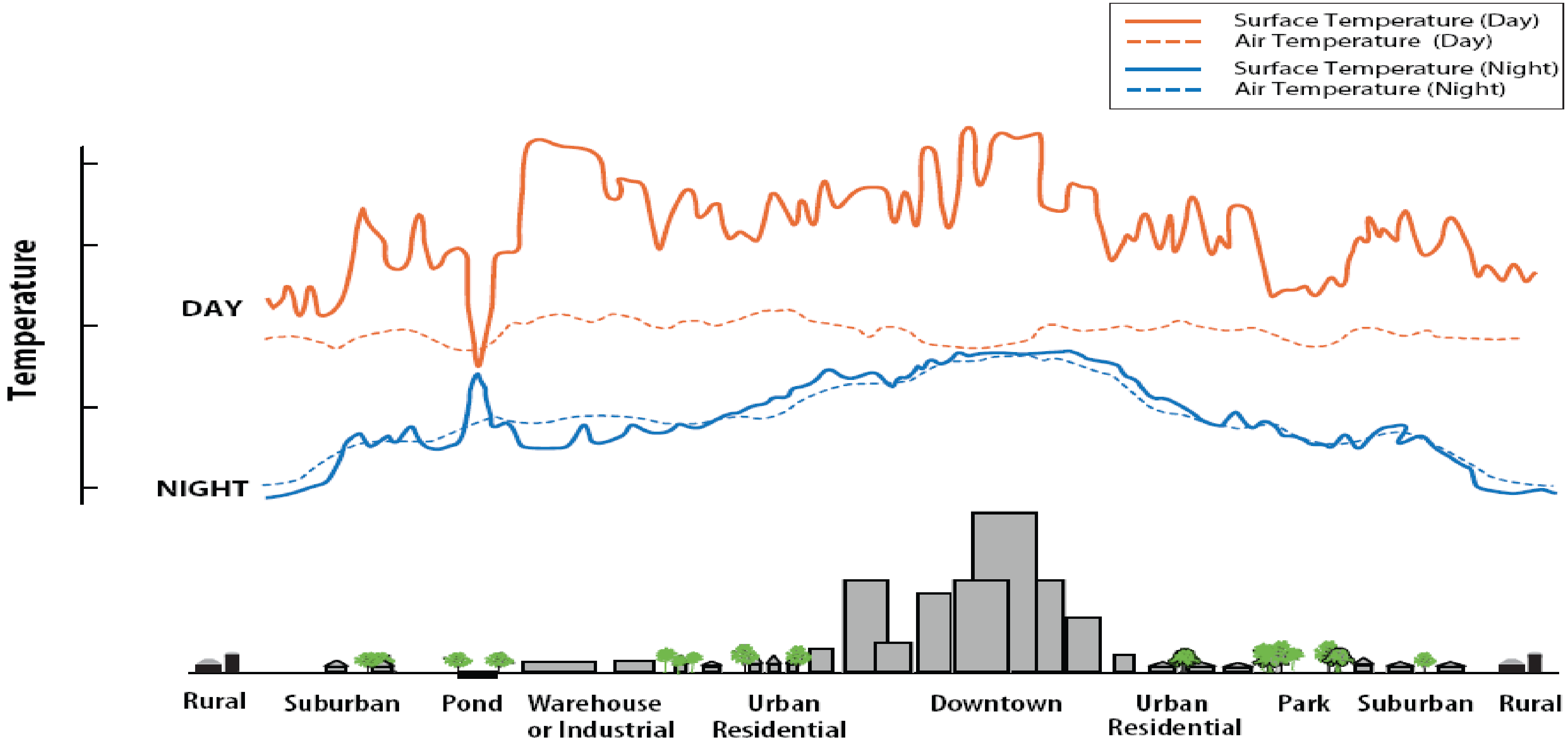
Causes of the UHI:

- 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.

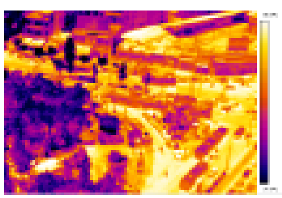
Cross-section of a typical UHI profile

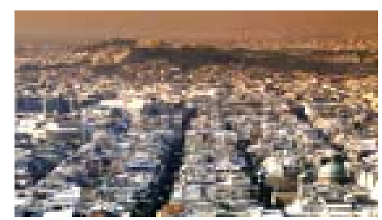


UHI impacts

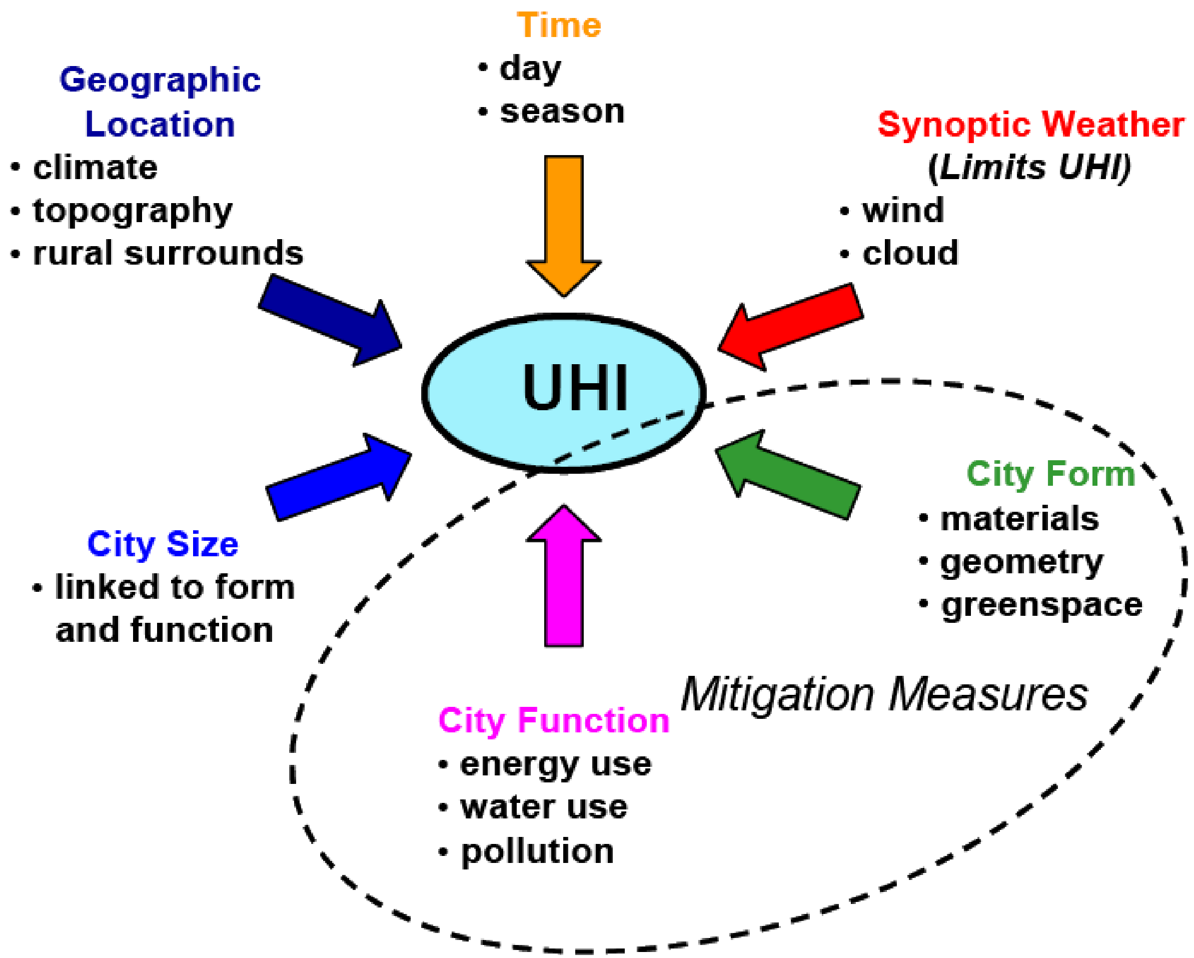
Urban Heat Islands

Thermal discomfort	Energy and economic concern	Air pollution
Increase of thermal discomfort especially for sensitive population	Increase of energy consumption for cooling	Increased possibility of smog
Increase of extreme temperatures during heat waves	Increase of peak load for cooling	Increased CO2 emissions
	Decrease of AC performance	

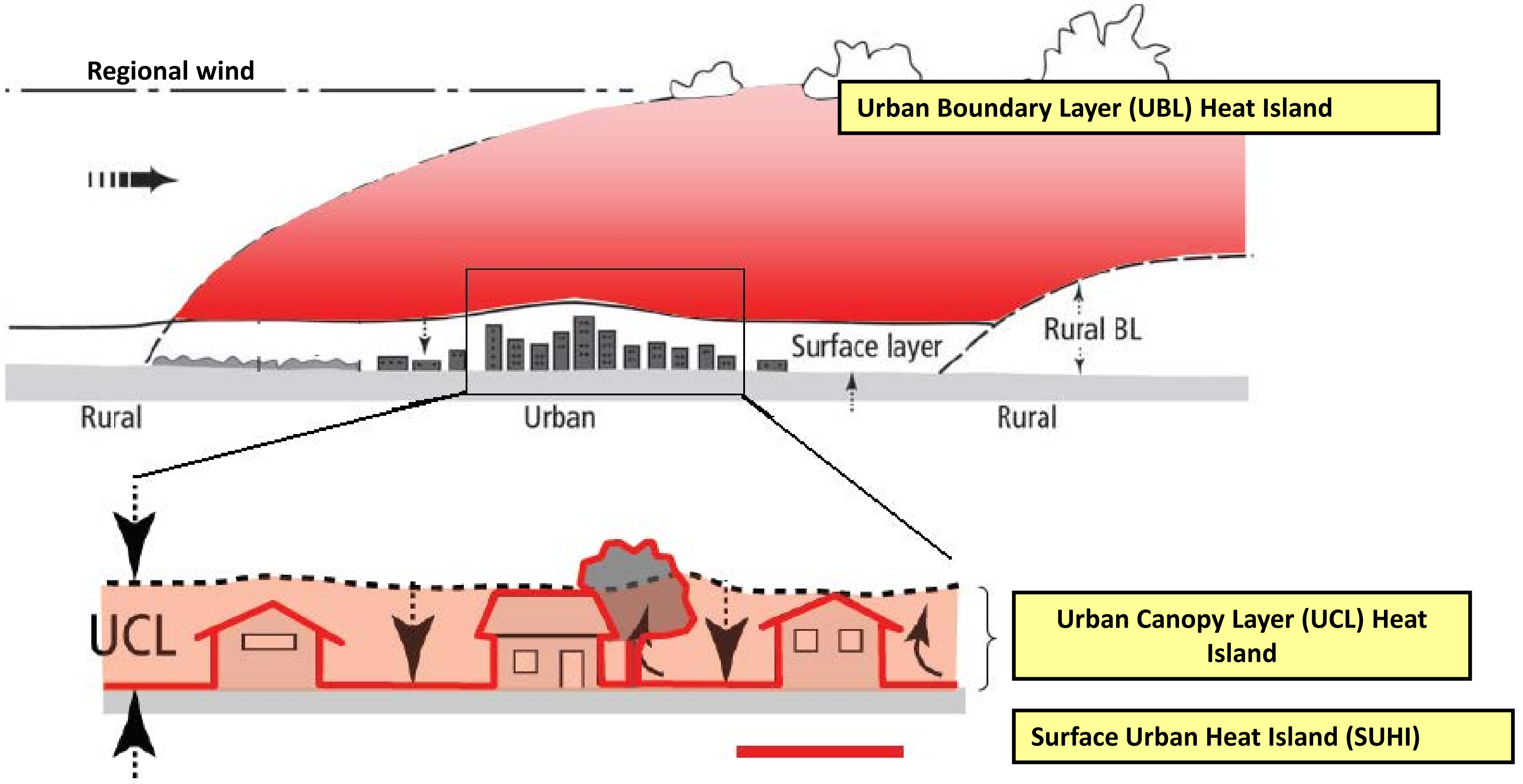




Factors affecting urban heat island intensity



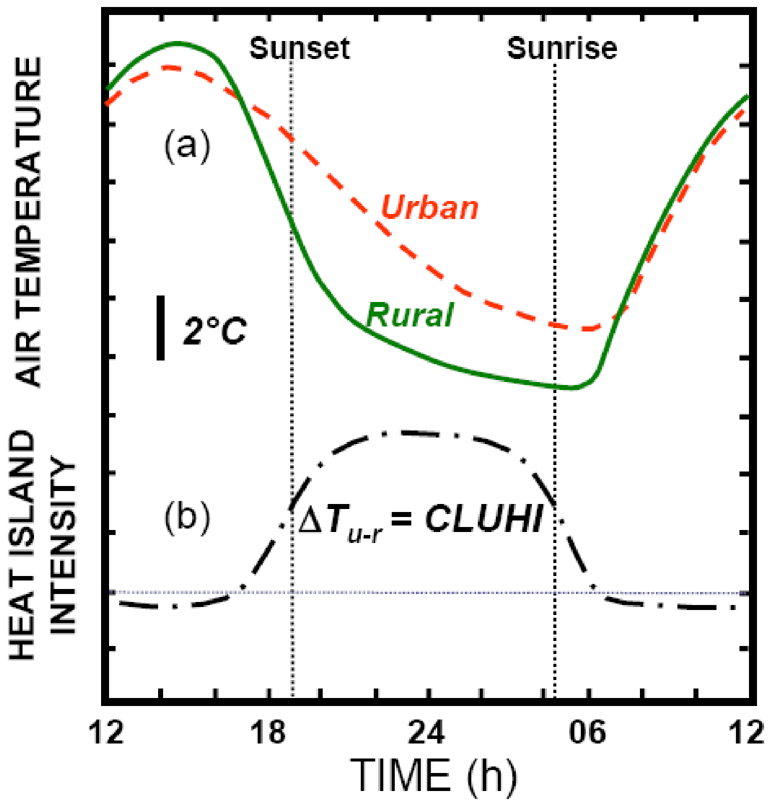
Urban heat islands: Three main types



Heat island intensity

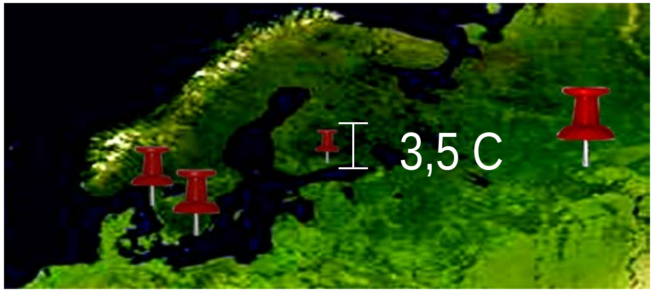
= the measure of the strength or magnitude of the heat island

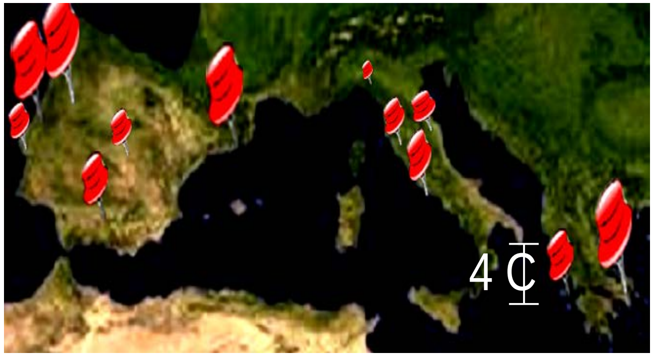
UHII = $T_{air,urban} - T_{air,rural}$



- 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

Source: Re-drawn from Oke (1987) Boundary Layer Climates (in Mills, 2004)



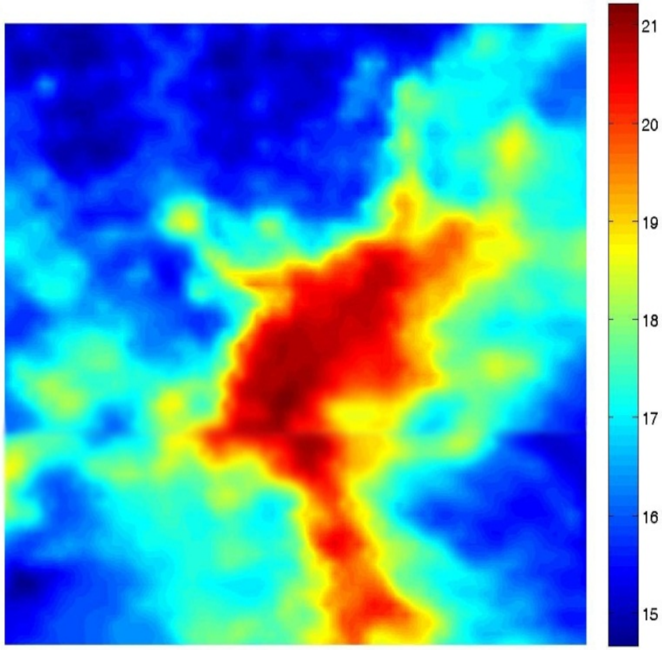


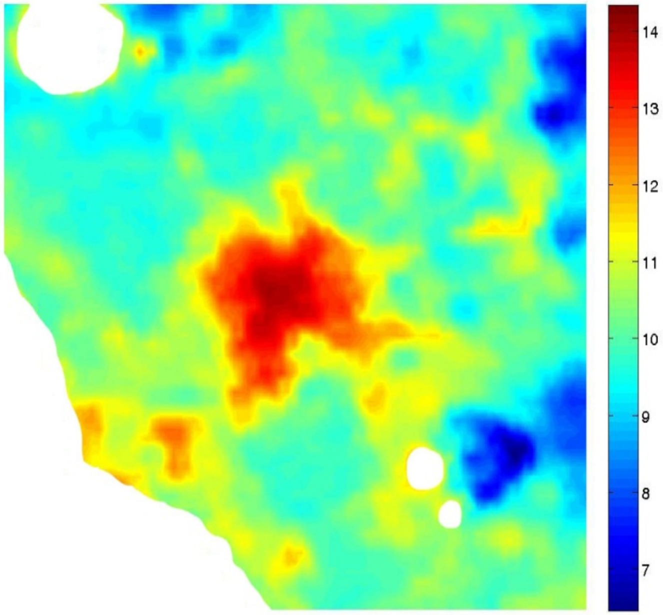
Heat Island is a very well documented phenomenon in Europe present in almost all latitudes.

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.

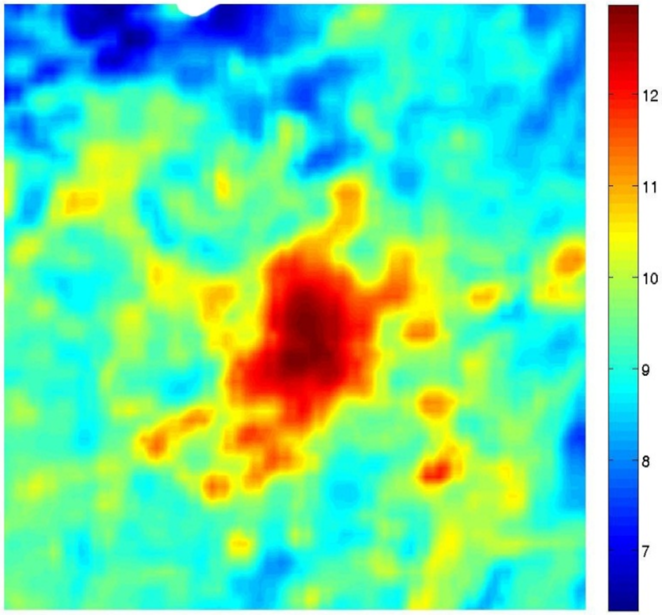
Surface UHI (SUHI)
Cairo (left) - Rome (right)

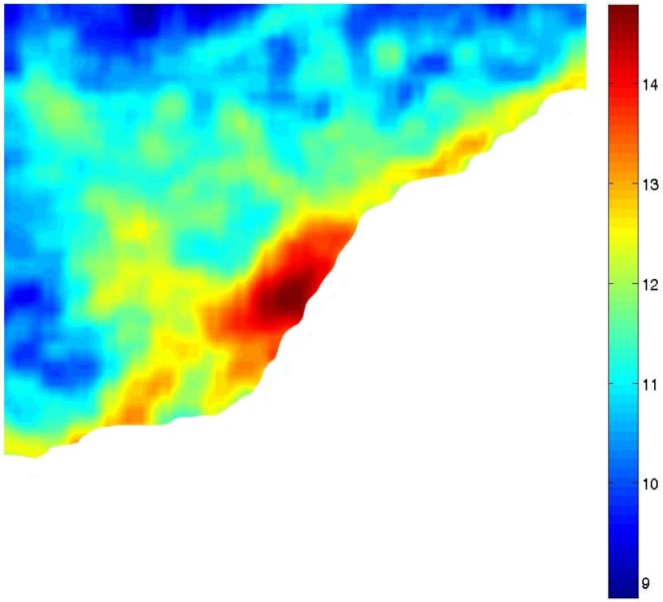




Source: Chrysoulakis, 2015

SUHI
Madrid (left) – Barcelona (right)



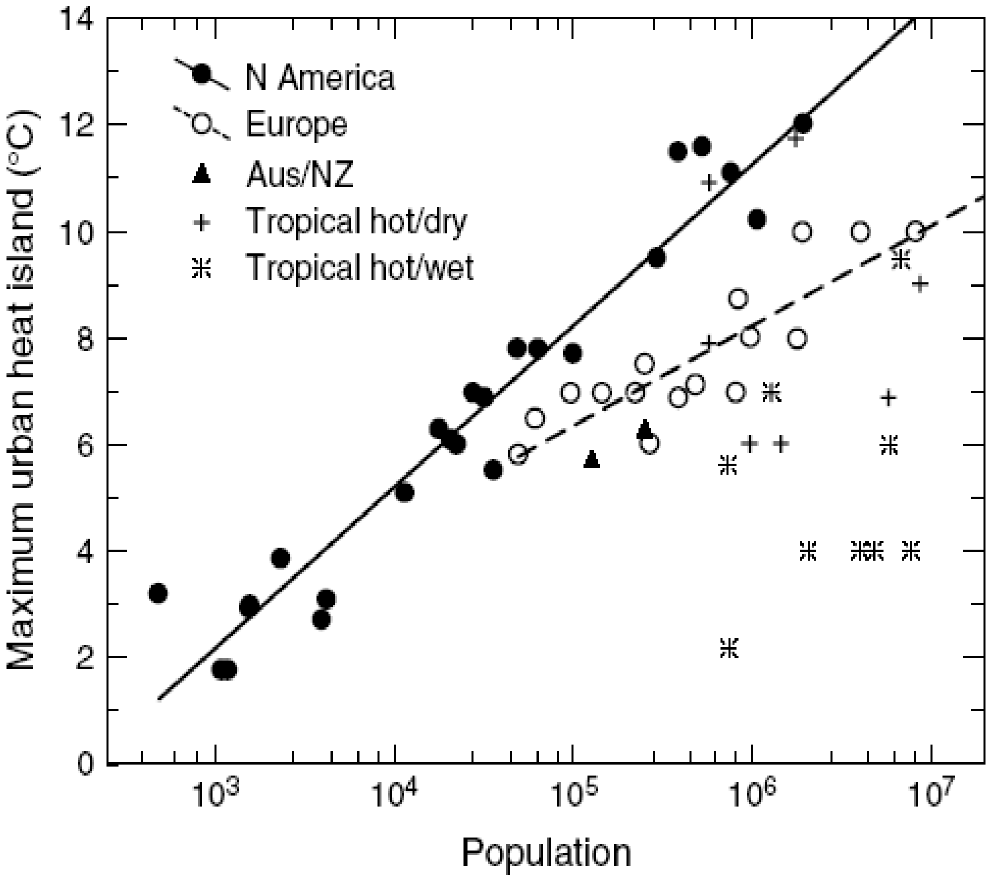


Source: Chrysoulakis, 2015

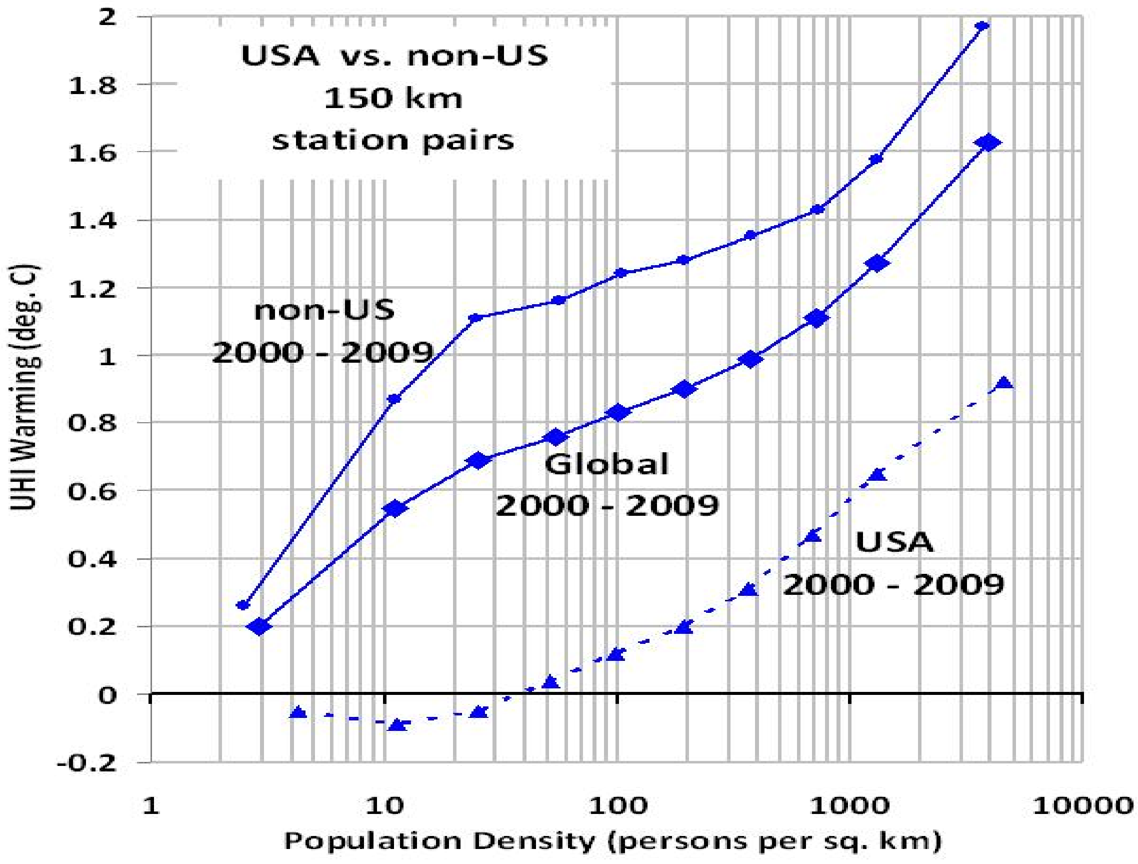
IMPORTANT

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

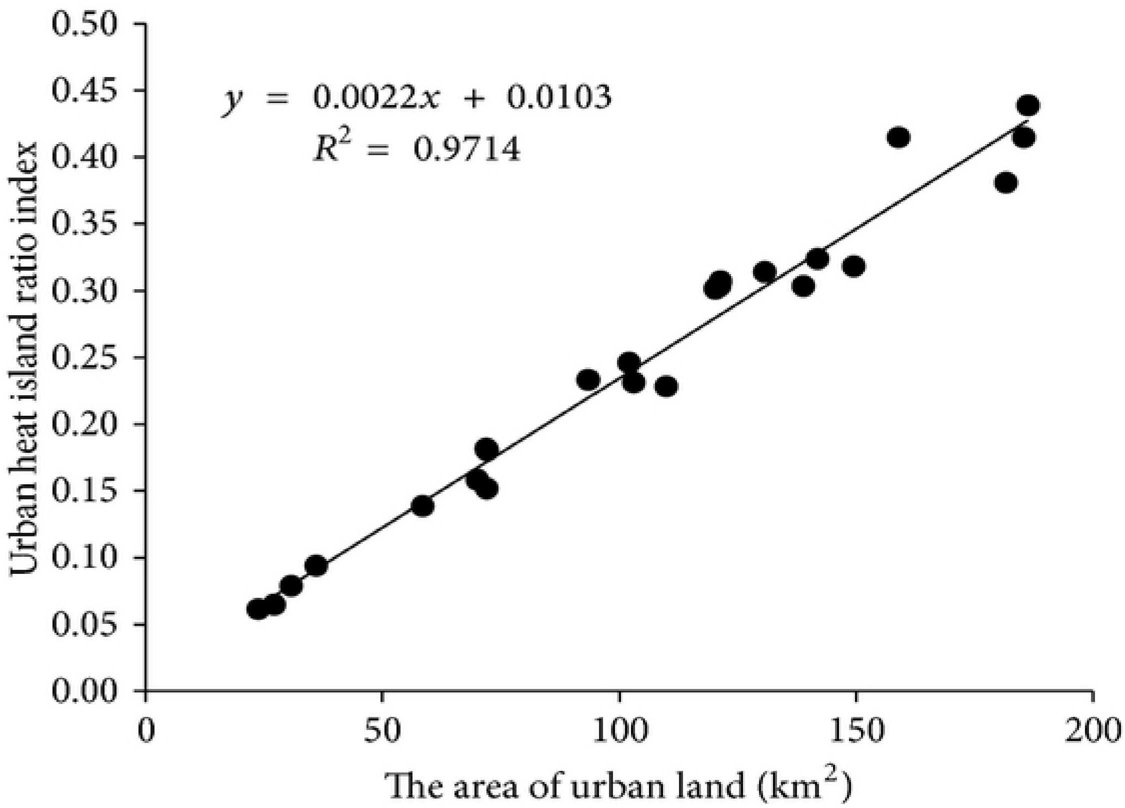
UHI dependence on urban population



UHI dependence on urban population density



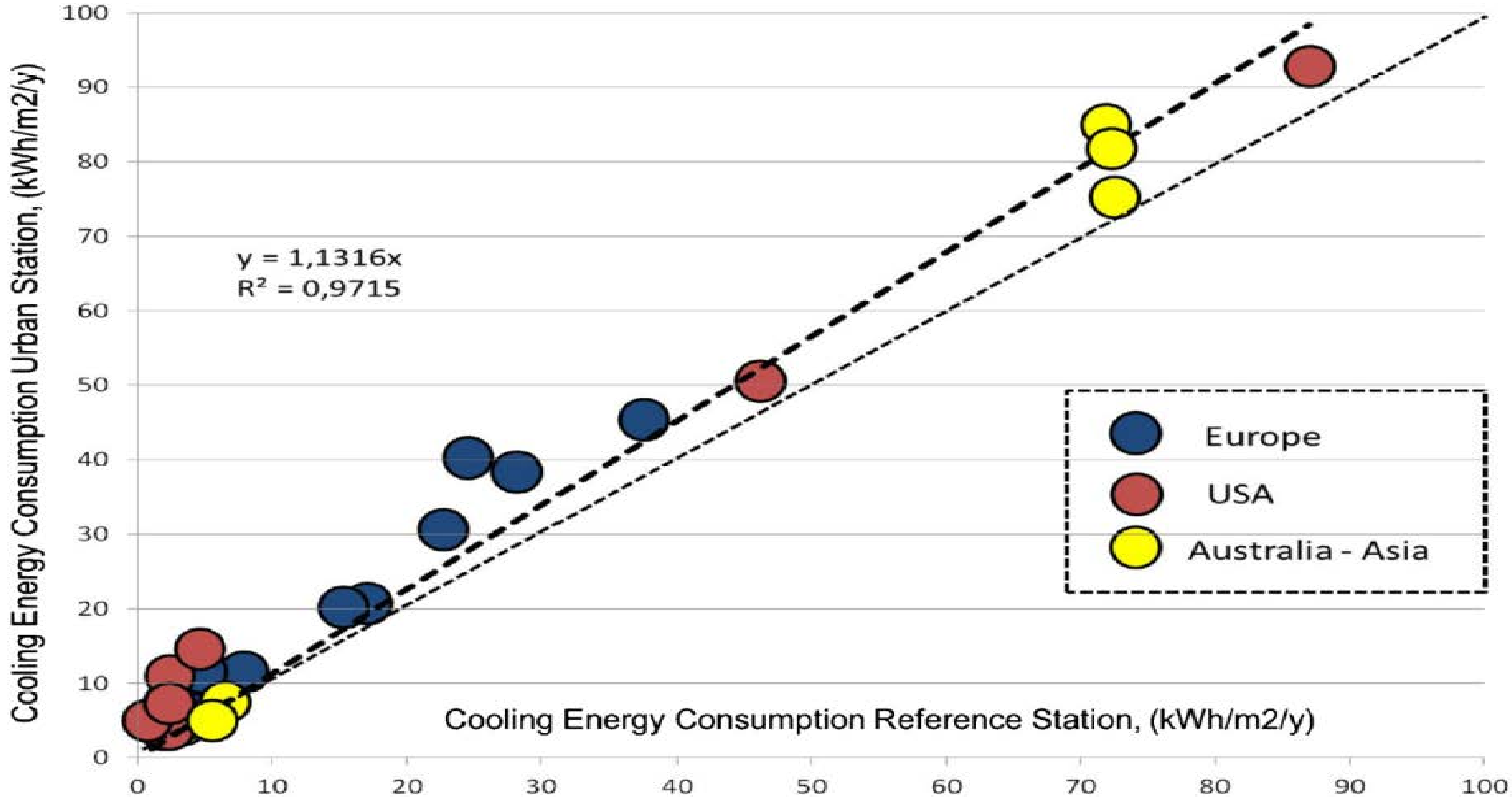
Source: Spencer: Global Urban Heat Island Effect Study – An Update



The relationship between urban land area and URI.

Source: Zhi Qiao, Guangjin Tian, Lixiao Zhang, and Xinliang Xu Influences of Urban Expansion on Urban Heat Island in Beijing during 1989–2010, Advances in Meteorology, Volume 2014 (2014), Article ID 187169, 11 pages

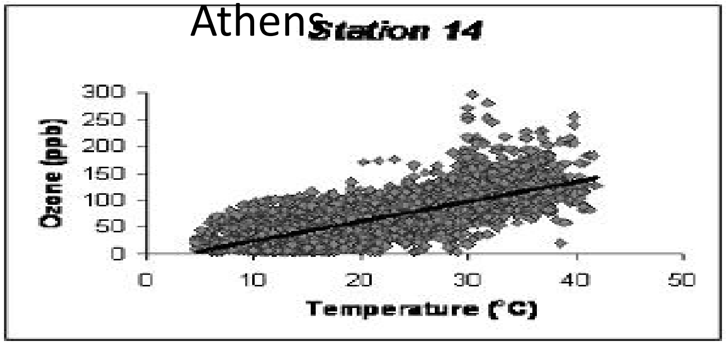
Cooling energy needs and UHI

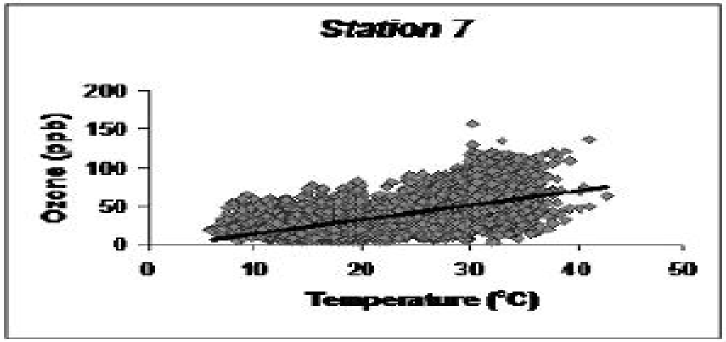


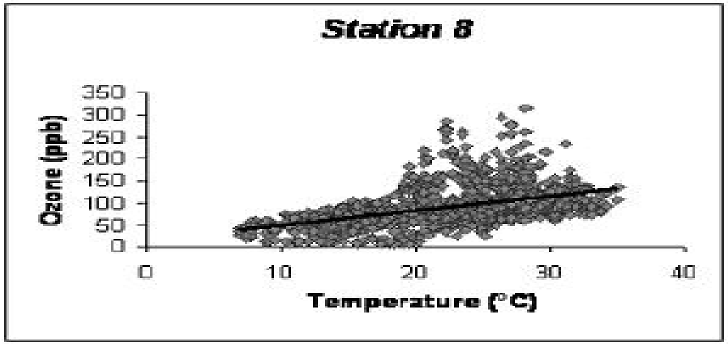
On the average the cooling load of typical urban buildings is by 13% higher compared to similar buildings in rural areas, with an increase of cooling load of roughly 20% per each °C more of urban heat island intensity.

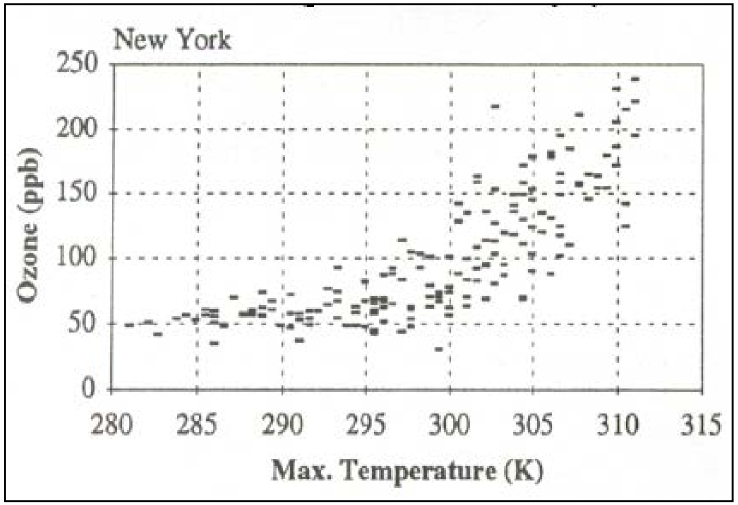
Santamouris (2014) Energy & Buildings
http://dx.doi.org/10.1016/j.enbuild.2014.07.022

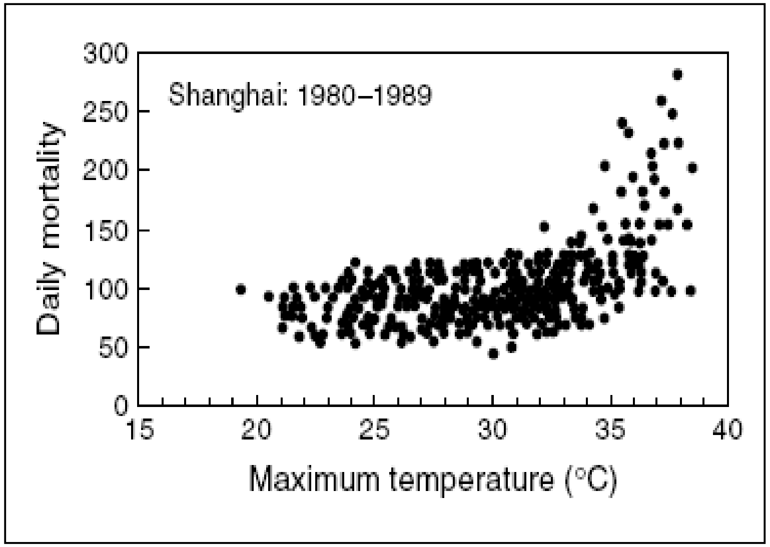
Air pollution vs Temperature



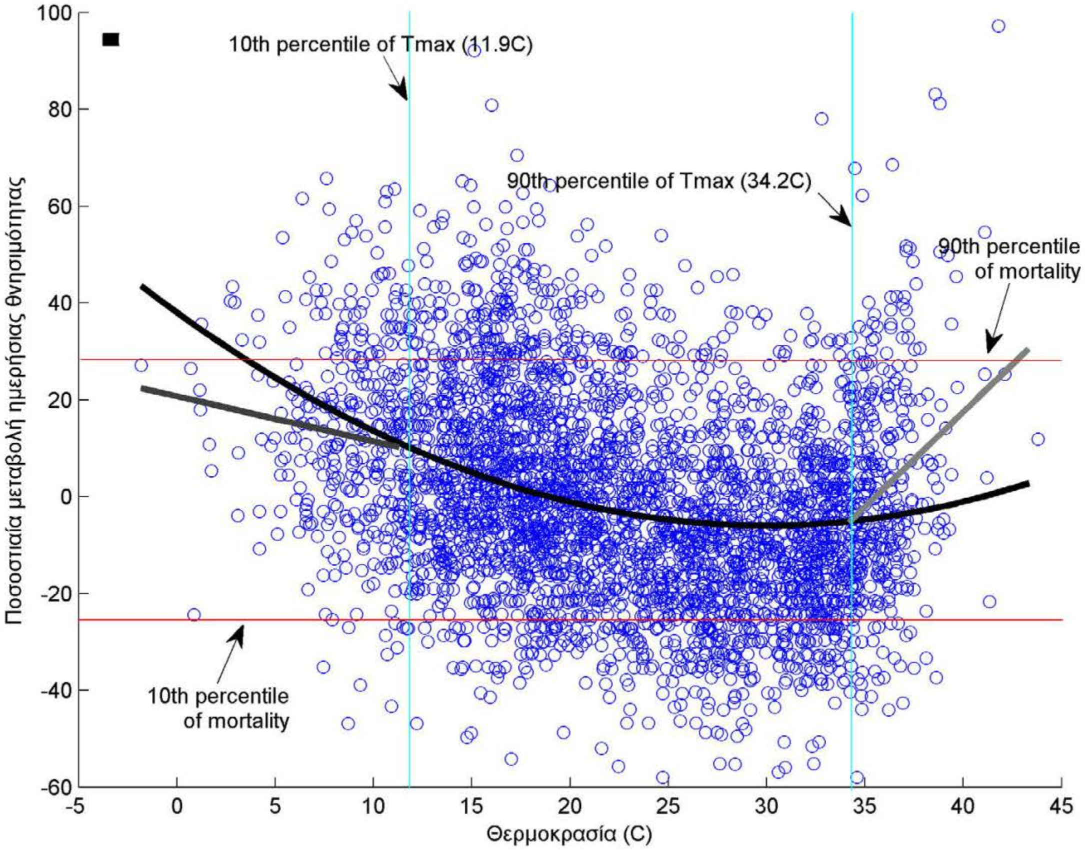








Increase of daily mortality vs temperature (for Athens)

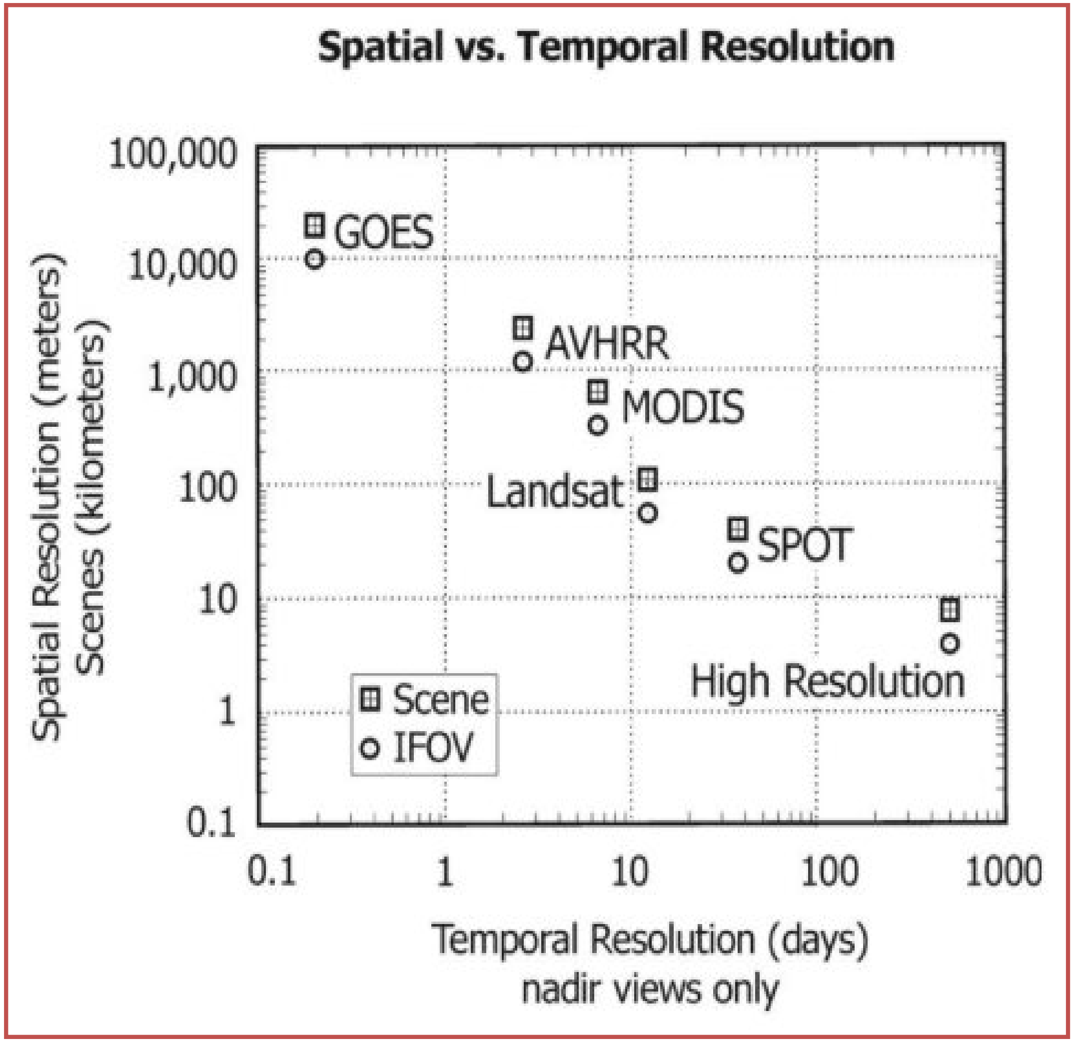


Source: Santamouris and Cartalis, 2017

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.

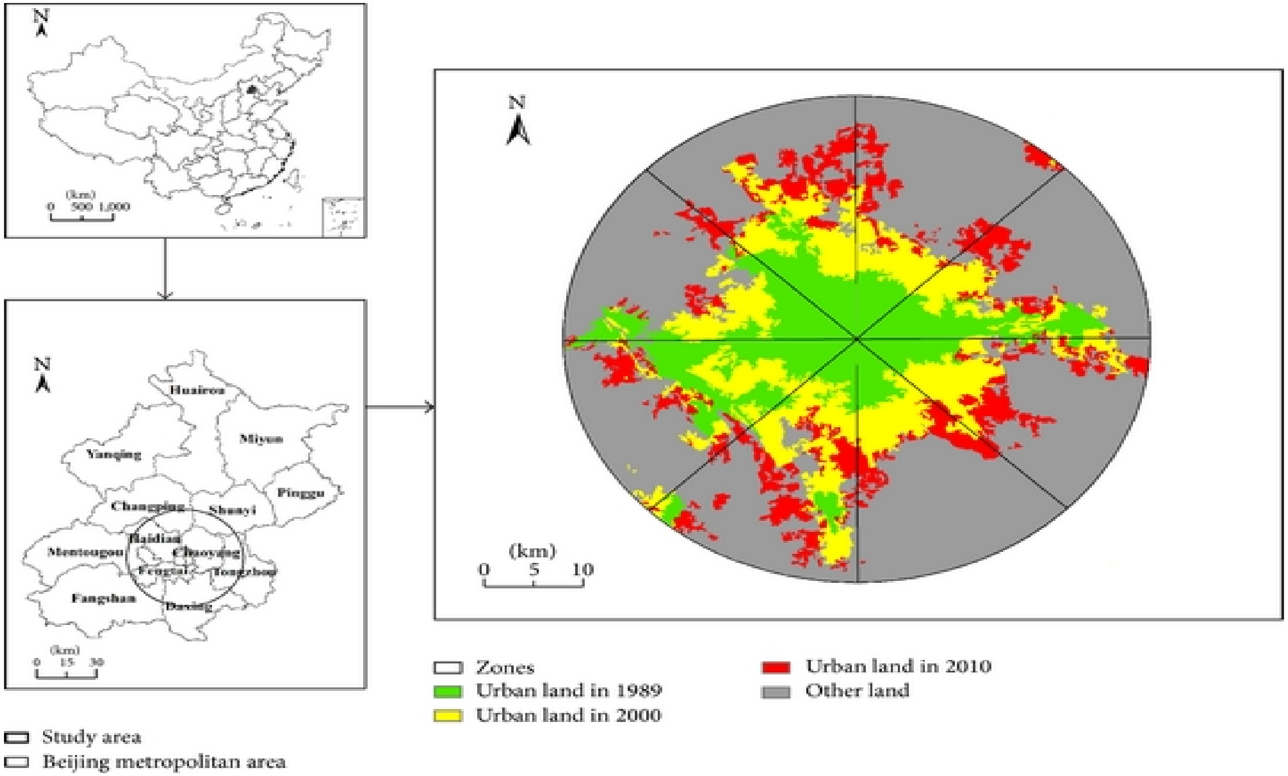
Part V: Estimating LST

Step 1. Develop a data base for your city

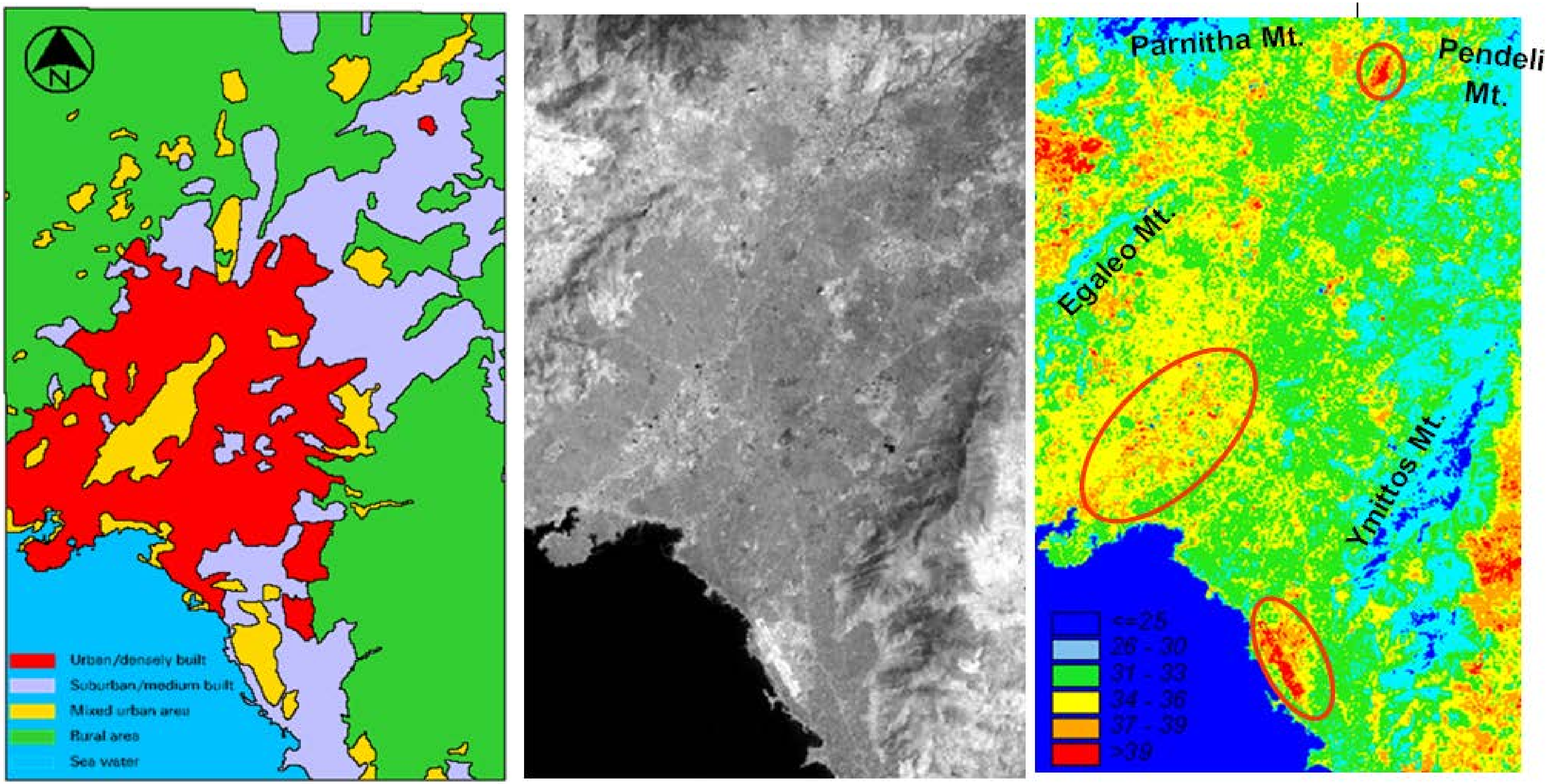
Climate data for Beijing (normals 1971–2000, extremes 1961–2000) [hide]													
Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Record high °C (°F)	14.3 (57.7)	19.8 (67.6)	29.5 (85.1)	33.0 (91.4)	38.3 (100.9)	42.6 (108.7)	41.9 (107.4)	38.3 (100.9)	35.0 (95)	31.0 (87.8)	23.3 (73.9)	19.5 (67.1)	42.6 (108.7)
Average high °C (°F)	1.8 (35.2)	5.0 (41)	11.6 (52.9)	20.3 (68.5)	26.0 (78.8)	30.2 (86.4)	30.9 (87.6)	29.7 (85.5)	25.8 (78.4)	19.1 (66.4)	10.1 (50.2)	3.7 (38.7)	17.9 (64.1)
Average low °C (°F)	−8.4 (16.9)	−5.6 (21.9)	0.4 (32.7)	7.9 (46.2)	13.6 (56.5)	18.8 (65.8)	22.0 (71.6)	20.8 (69.4)	14.8 (58.6)	7.9 (46.2)	0.0 (32)	−5.8 (21.6)	7.2 (45.0)
Record low °C (°F)	−18.3 (−0.9)	−27.4 (−17.3)	−15 (5)	−3.2 (26.2)	2.5 (36.5)	9.8 (49.6)	15.3 (59.5)	11.4 (52.5)	3.7 (38.7)	−3.5 (25.7)	−12.5 (9.5)	−18.5 (−1.3)	−27.4 (−17.3)
Precipitation mm (inches)	2.7 (0.106)	4.9 (0.193)	8.3 (0.327)	21.2 (0.835)	34.2 (1.346)	78.1 (3.075)	185.2 (7.291)	159.7 (6.287)	45.5 (1.791)	21.8 (0.858)	7.4 (0.291)	2.8 (0.11)	571.8 (22.51)
Avg. precipitation days (≥ 0.1 mm)	1.8	2.3	3.3	4.3	5.8	9.7	13.6	12.0	7.6	5.0	3.5	1.7	70.6
% humidity	44	44	46	46	53	61	75	77	68	61	57	49	56.8
Mean monthly sunshine hours	194.1	194.7	231.8	251.9	283.4	261.4	212.4	220.9	232.1	222.1	185.3	180.7	2,670.8
Percent possible sunshine	65	65	63	64	64	59	47	52	63	64	62	62	60

Source: China Meteorological Administration [1], all-time extreme temperature [2]

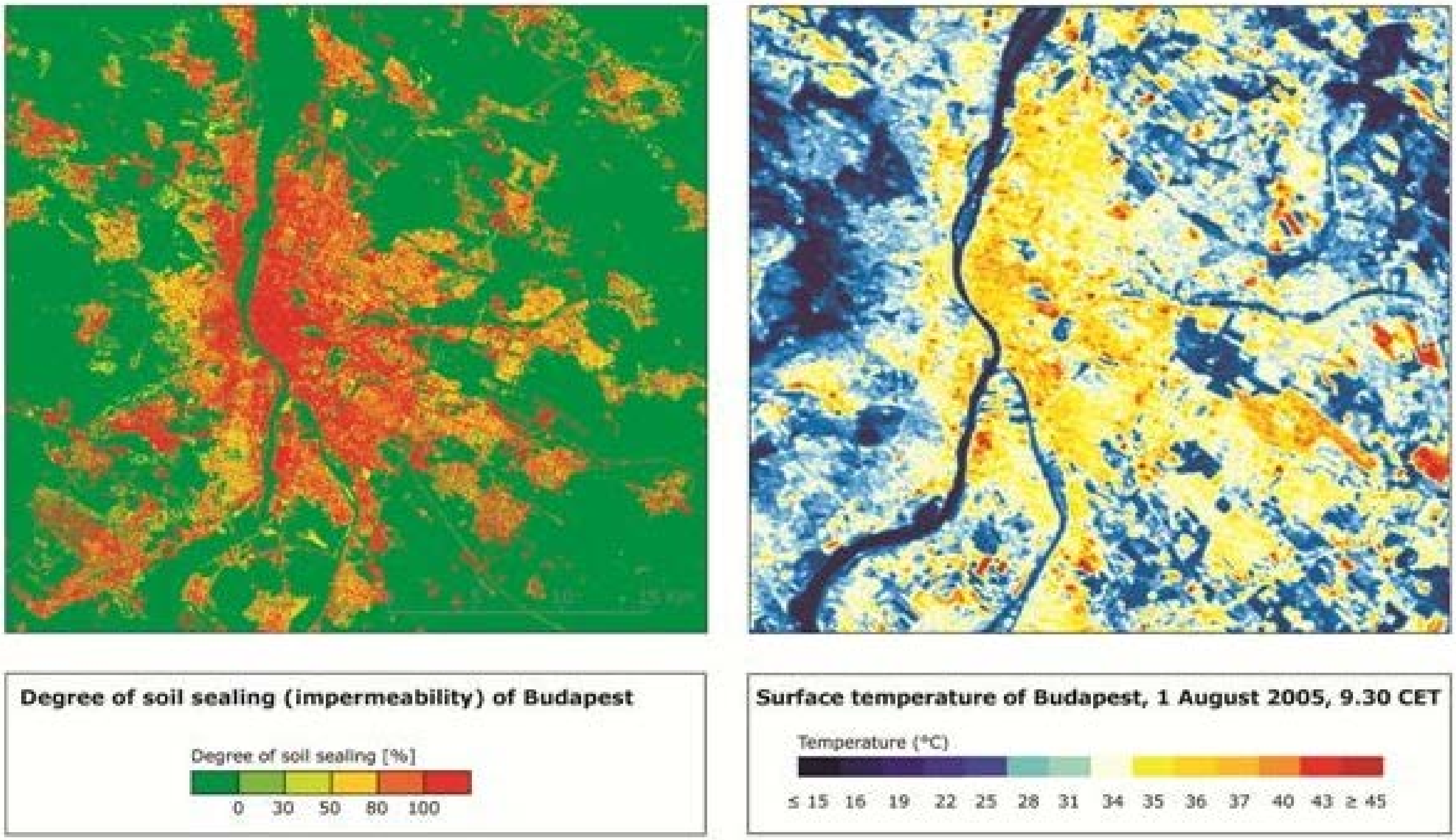
Step 2. Define Land cover (and its changes)



The spatial distribution of urban land in Beijing during 1989–2010.



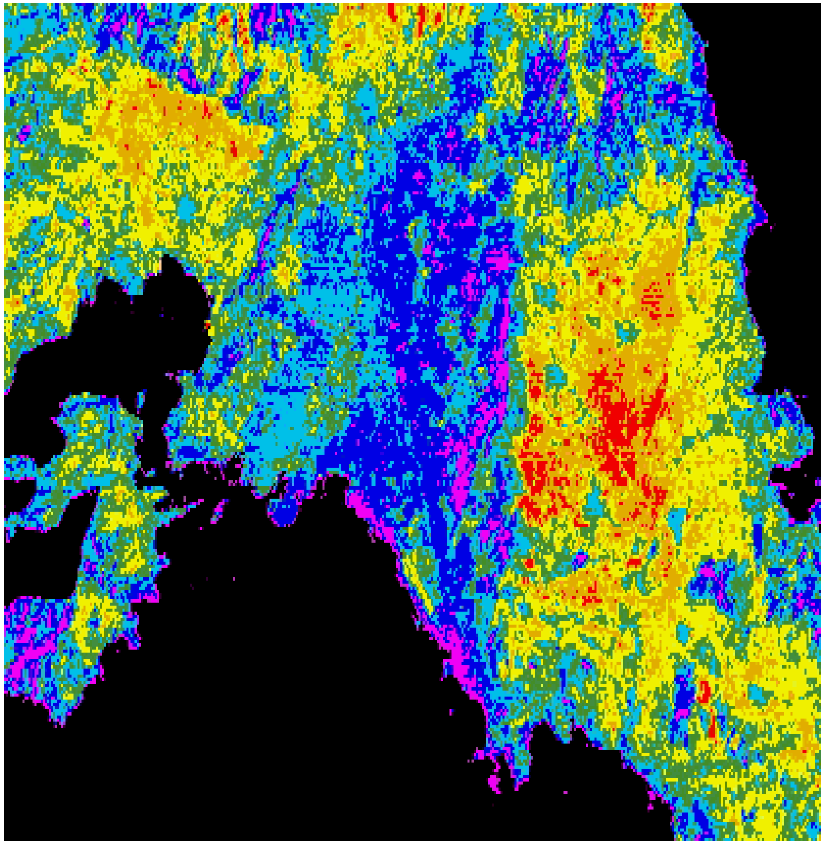
Left to right: Land cover, satellite image in the visible, thermal image



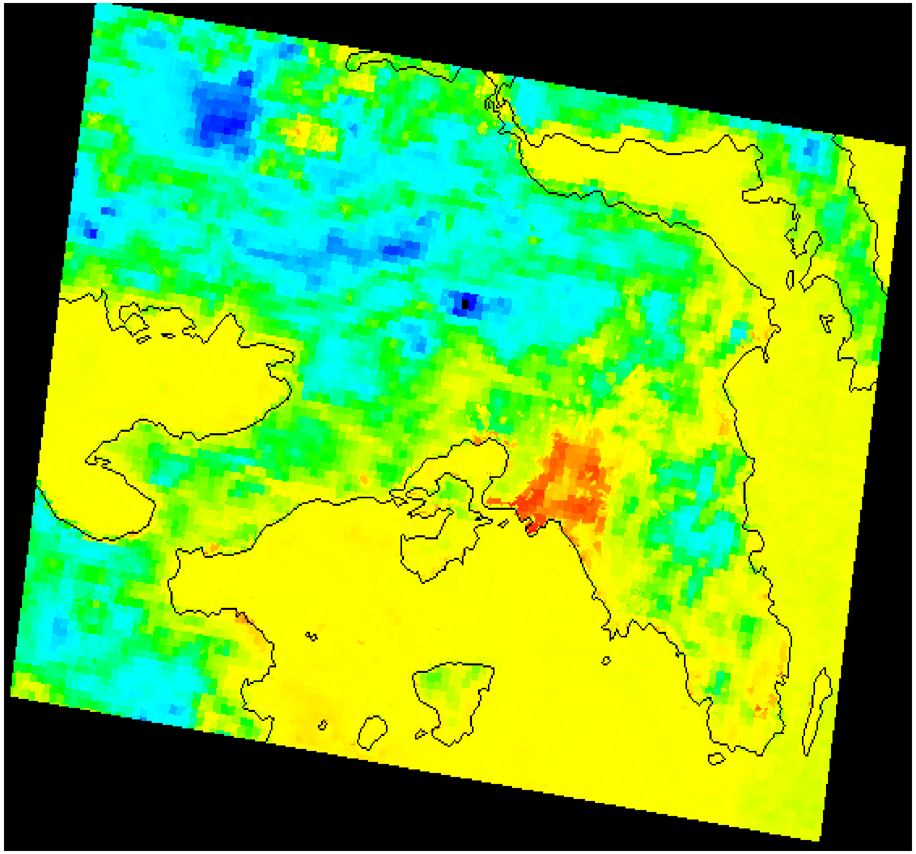
Source: Gábor, P., Jombach, S. and Ongjerth, R. , 2008

Step 3. Choose the appropriate spatial (and temporal) resolution

120m resolution

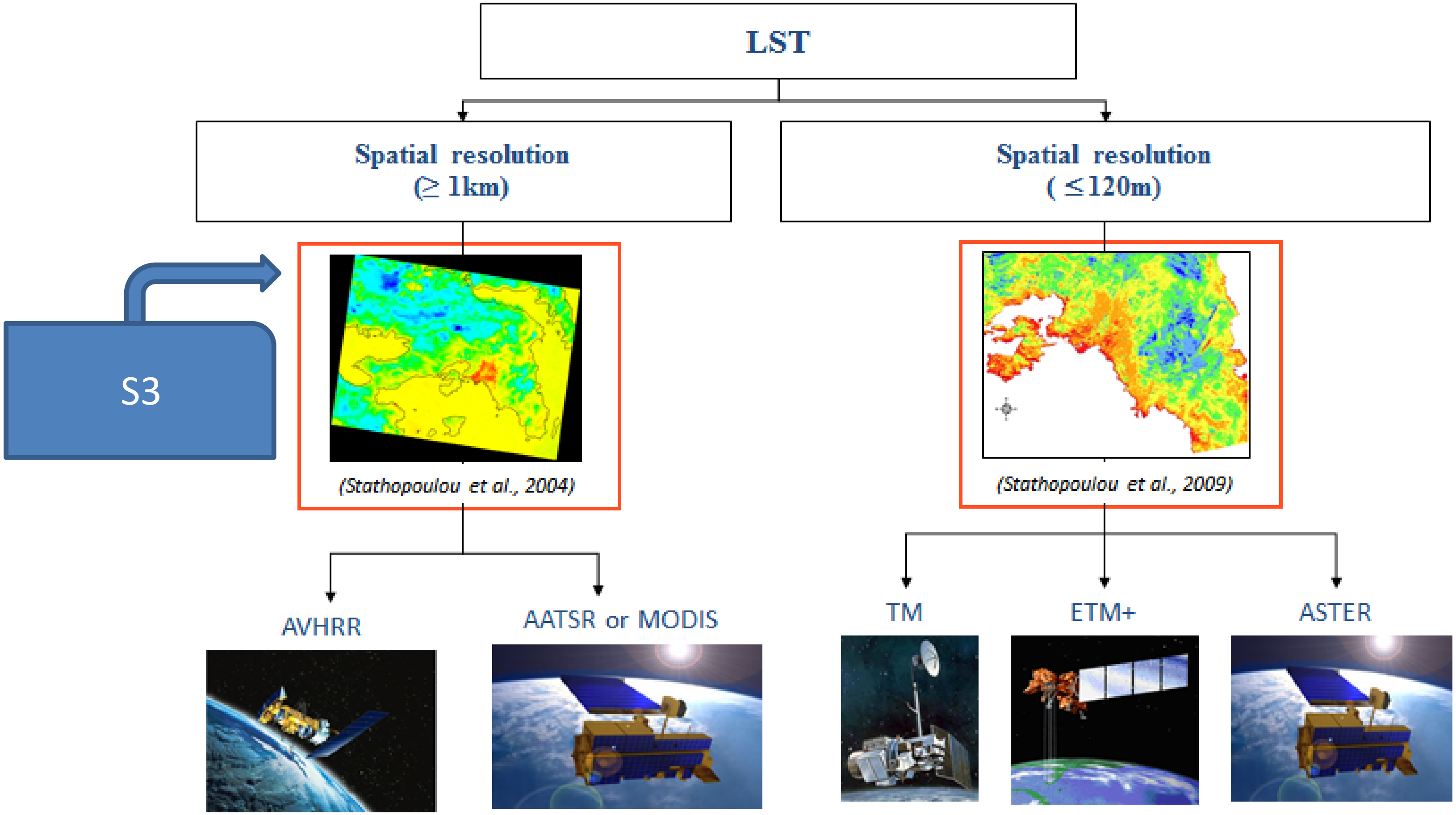


1.1 km resolution

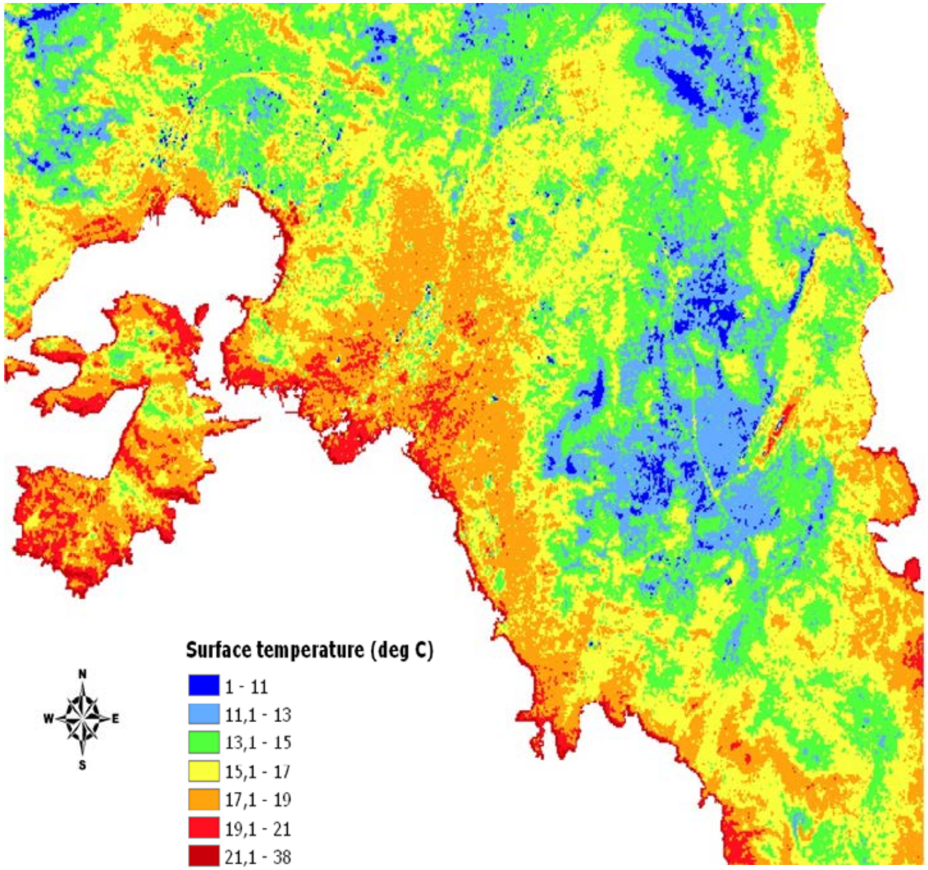


Source: processing by C.Cartalis

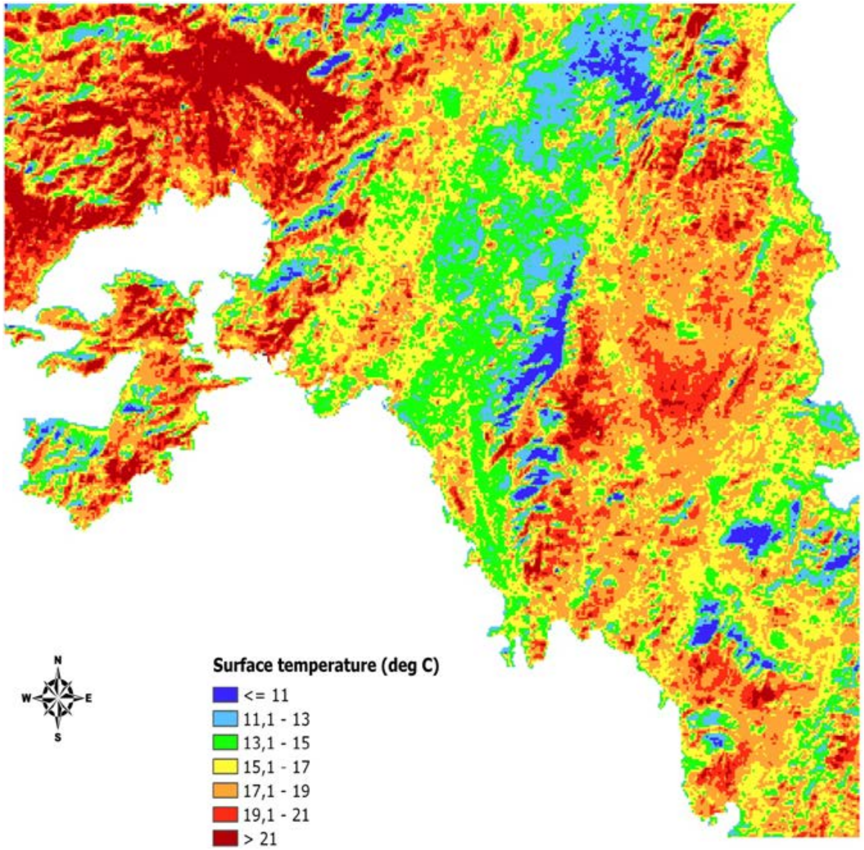
Step 4. Choose the right satellite mission – Merge satellite data



Step 5. What time of the day? (the impact of thermal capacity)



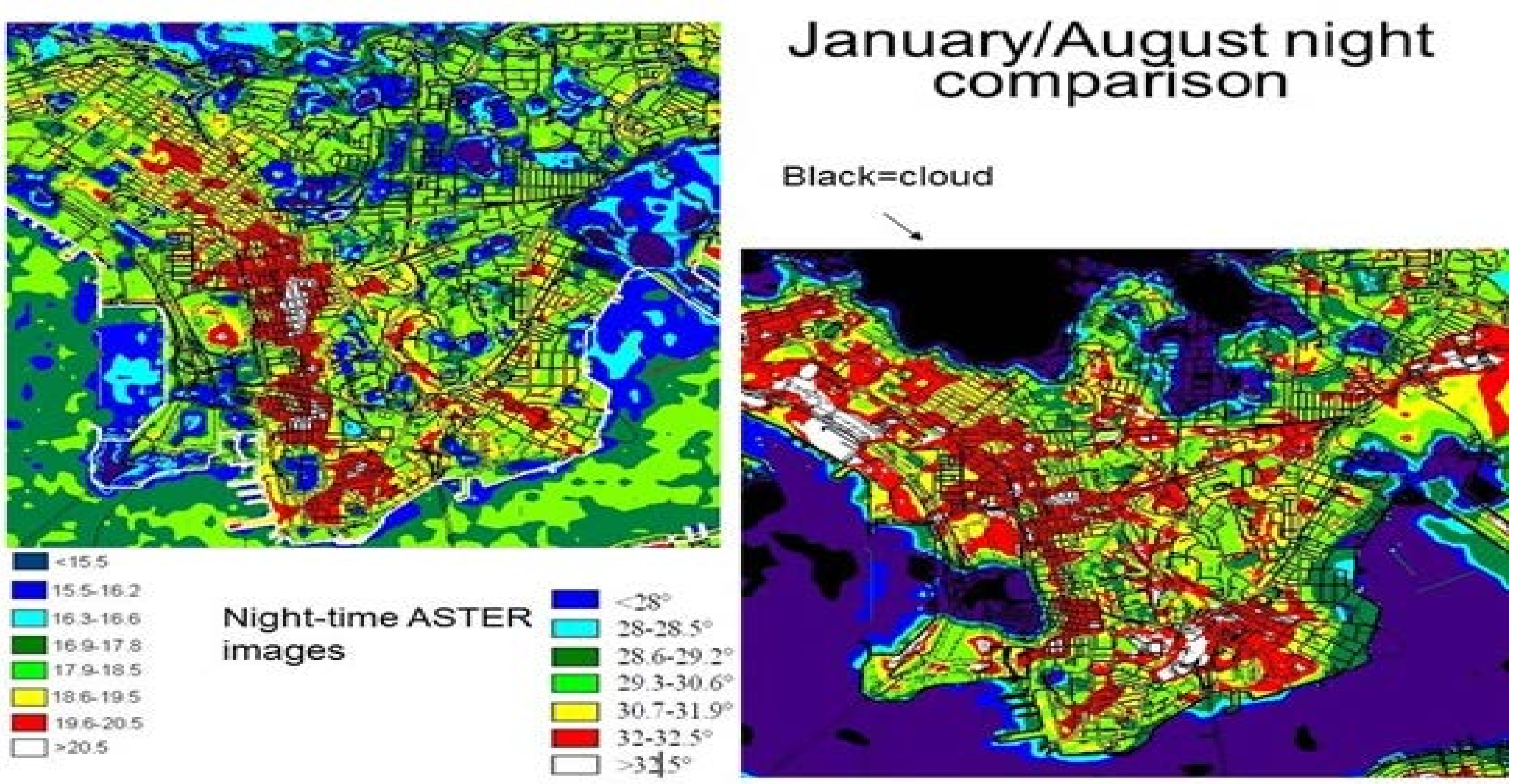
22:32 local time



10:30 local time

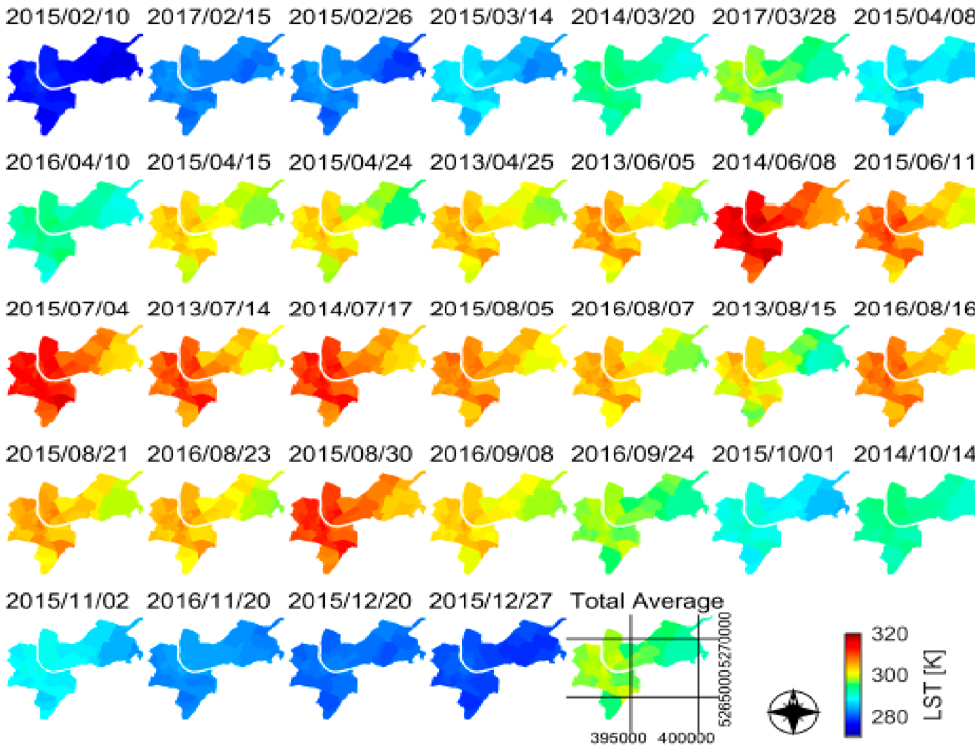
Source: processing by C. Cartalis

Step 6. Which period of the year?



Source: The Hong Kong Polytechnic University

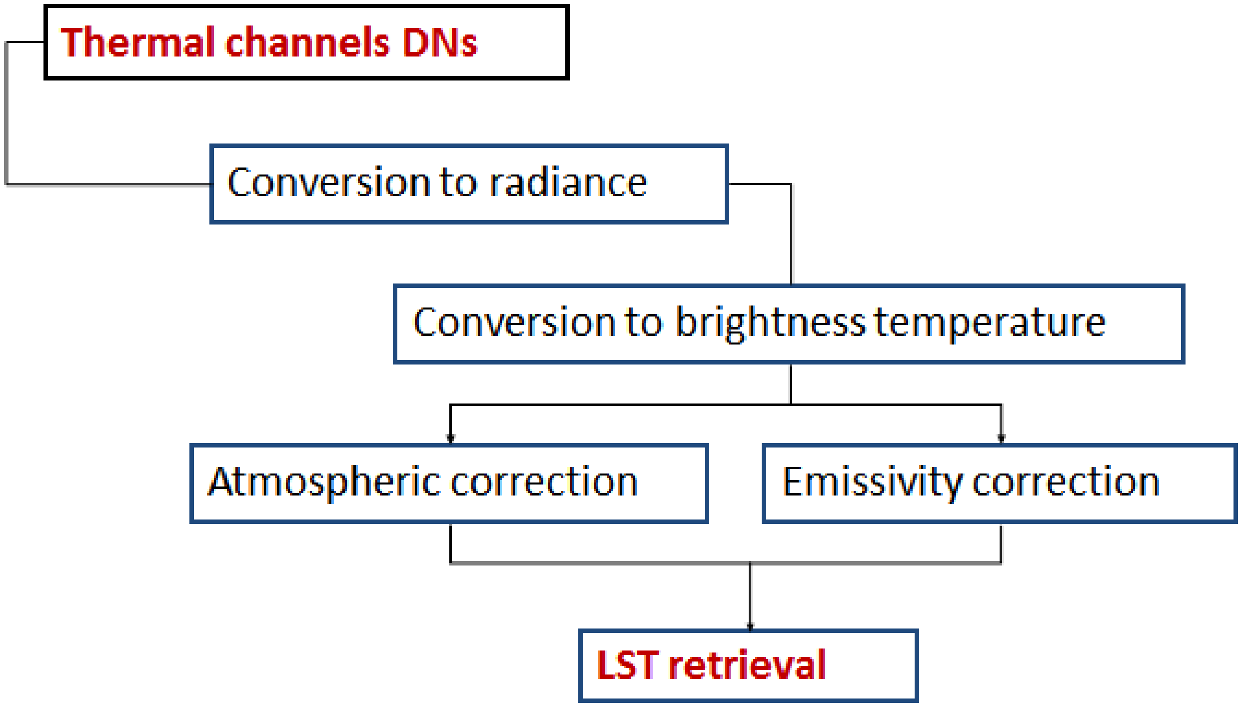
Step 6. Which period of the year?



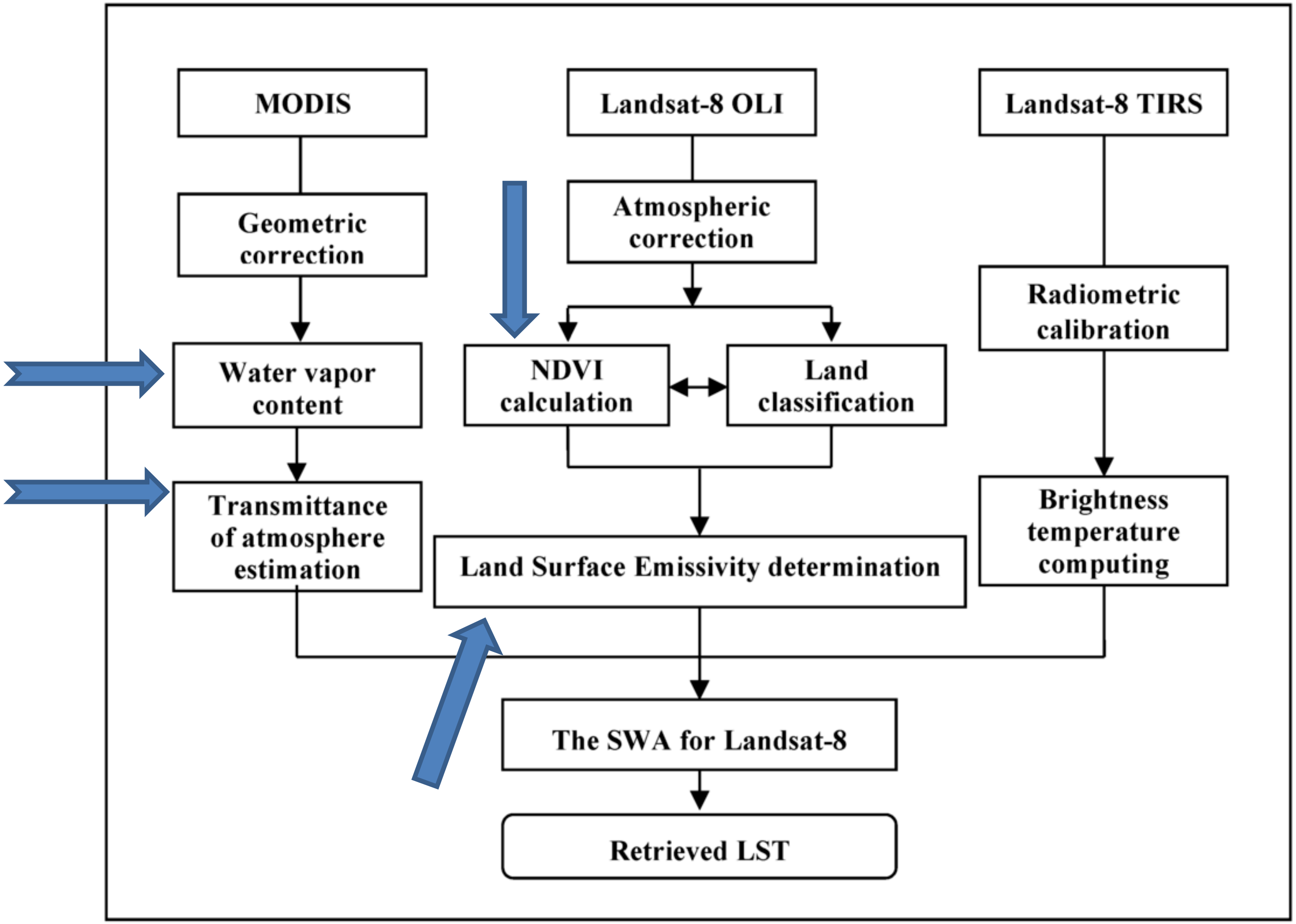
LST averages retrieved from L8 TIRS of each residential district for 32 days between 2013 and 2017 of the Canton Basel-Stadt. The scenes are ordered after the DOY of acquisition.

Source: Wicki, A. and Parlow, E., 2017

Step 7. Convert and Retrieve



Overall LST accuracy: ±2 Kelvin


MODIS
Landsat-8 OLI
Landsat-8 TIRS
Geometric correction
Atmospheric correction
Radiometric calibration
Water vapor content
NDVI calculation
Land classification
Transmittance of atmosphere estimation
Land Surface Emissivity determination
Brightness temperature computing
The SWA for Landsat-8
Retrieved LST

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·W·cm^{-2}·sr·µm^{-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 λ is the wavelength of emitted radiance (λ = 11.5 µm), σ is the Boltzmann constant (1.38 × 10^{-23} J/K), and h is the Planck's constant (6.626 × 10^{-34} Js), C is the velocity of light (2.998 × 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 (land surface temperature) = Ti + c1 (Ti − Tj) + c2 (Ti − Tj) 2 + c0 + (c3 + c4*W) (1 − ε) + (c5 + c6*W) Δε where:

Ti and Tj : at-sensor brightness temperatures at the SW bands i and j (in Kelvin)

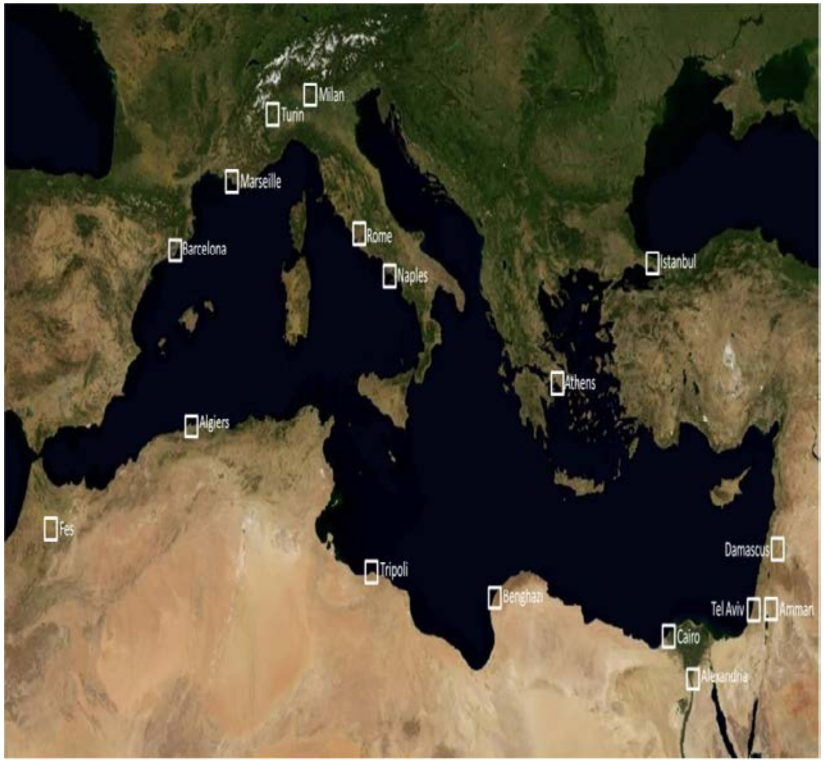
ε: the mean emissivity, ε = 0.5(εi + εj),

Δε: the emissivity difference, Δε = (εi − εj),

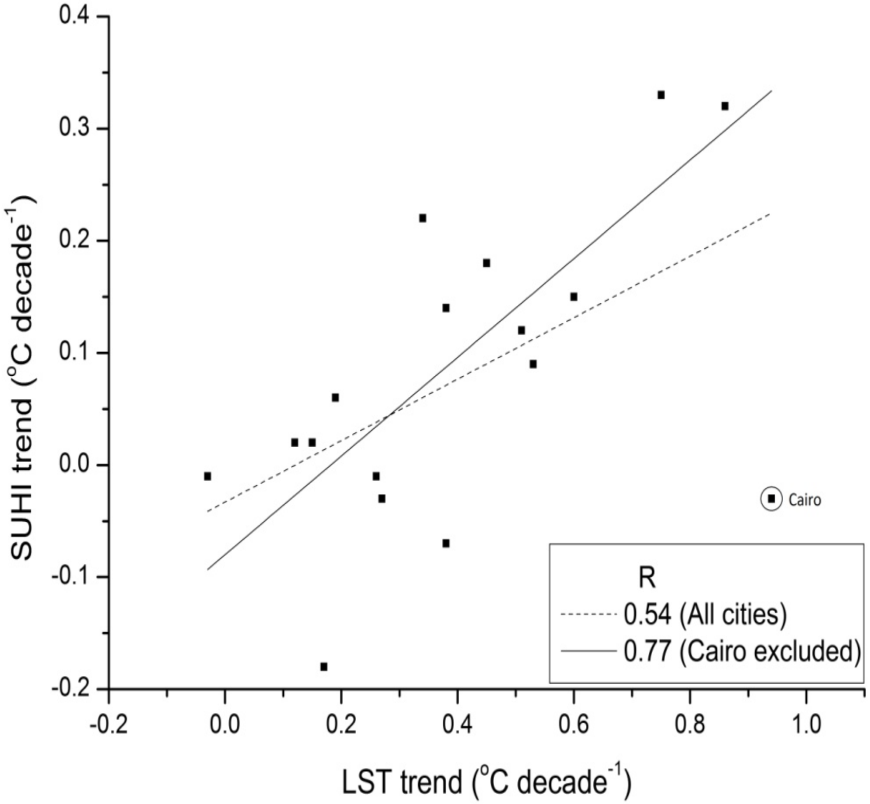
W is the total atmospheric water vapor content (in grams per square centimeter),

c0−c6: the SWT coefficients

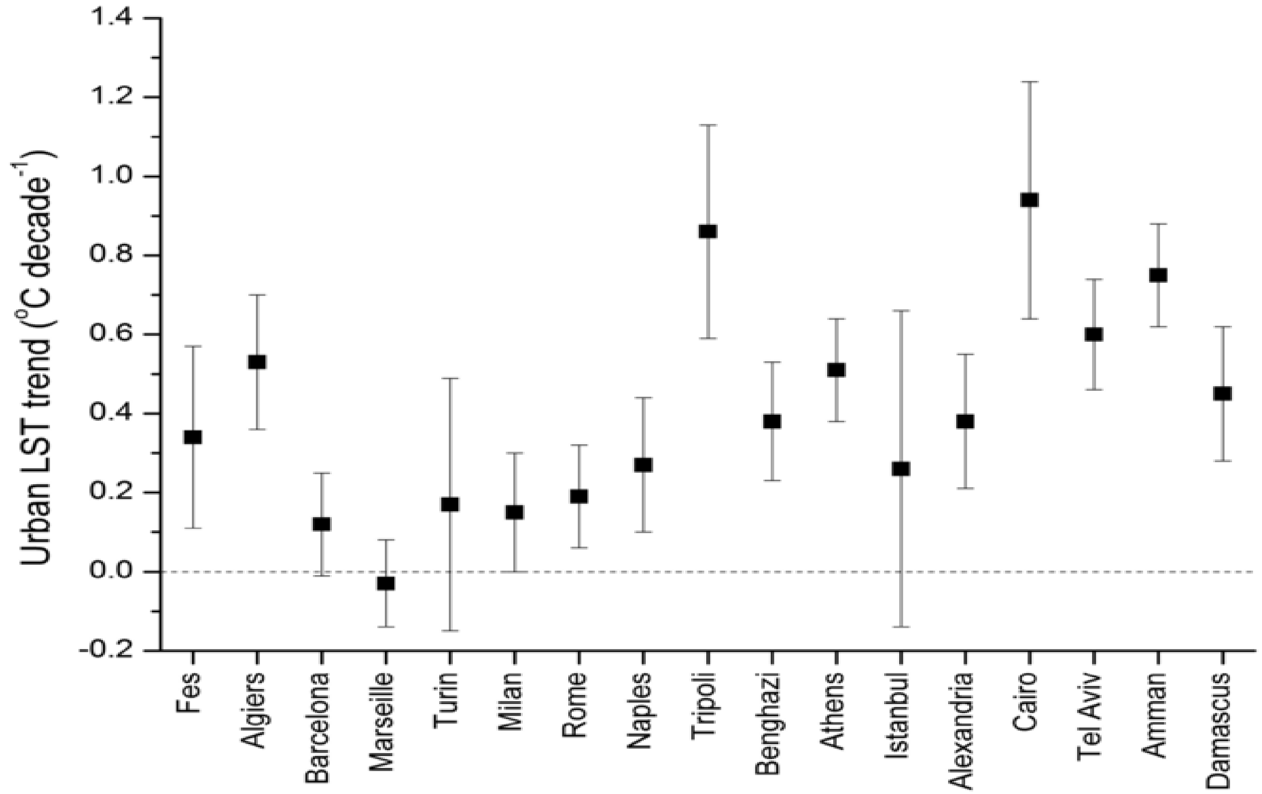
In the case of the MODIS sensors i and j are bands 31 and 32, at 10.780–11.280 μm and 11.770–12.270 μm respectively.



Milan
Turin
Marseille
Rome
Barcelona
Naples
Istanbul
Athens
Algiers
Fes
Damascus
Tripoli
Benghazi
Tel Aviv
Amman
Cairo
Alexandria

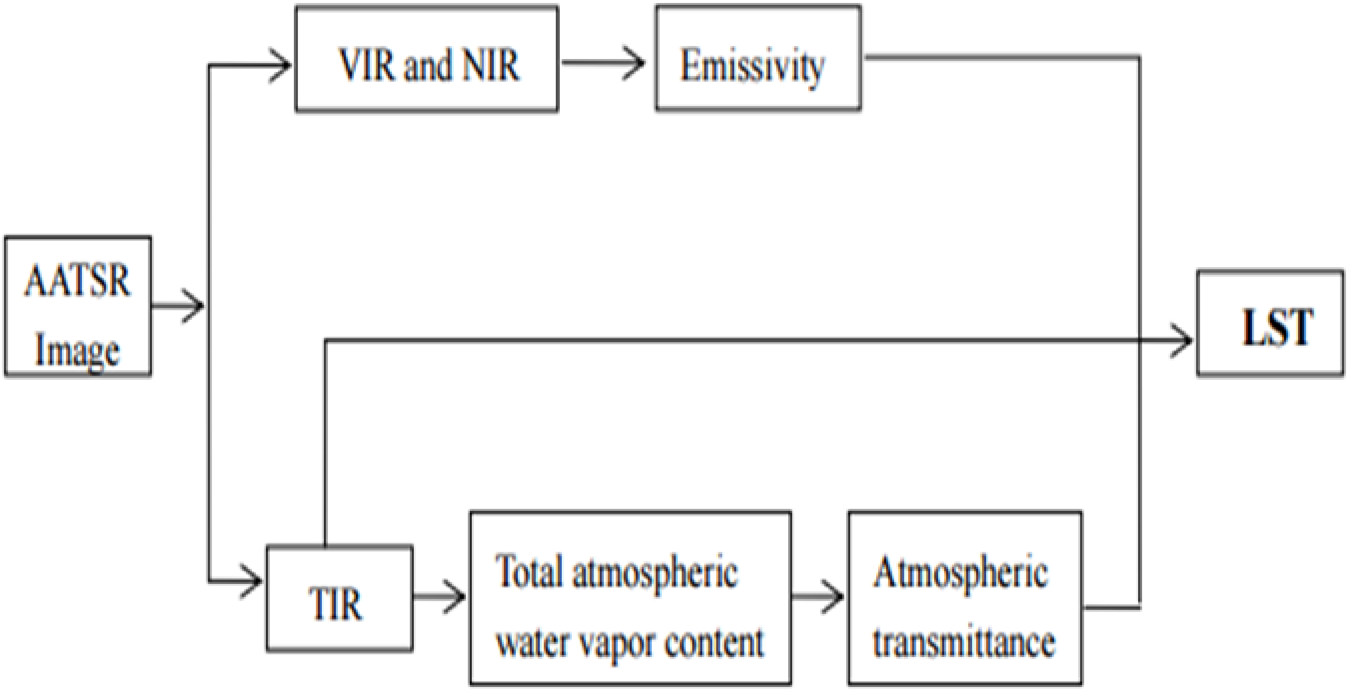


SUHI trend (°C decade⁻¹)
LST trend (°C decade⁻¹)
Cairo
R
0.54 (All cities)
0.77 (Cairo excluded)
0.4
0.3
0.2
0.1
0.0
-0.1
-0.2
-0.2
0.0
0.2
0.4
0.6
0.8
1.0



Source. Benas, N, Chrysoulakis, N., and Cartalis, C., 2016

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):

$$T_{Sentinel3,30} = T_{Sentinel3,1000} * T^{27/7/16}_{landsat,30} / T^{27/7/16}_{landsat,30 \to 1000}$$

$$T_{Sentinel3,30} = T_{Sentinel3,1000} * \varepsilon_{landsat,30} / \varepsilon_{landsat,30 \to 1000}$$

$T_{Sentinel3,30}$	Corrected image high spatial resolution
$T_{Sentinel3,1000}$	Initial image of low spatial resolution
$T^{27/7/16}_{landsat,30}$	Initial value of high spatial resolution (LANDSAT)
$T^{27/7/16}_{landsat,30 \to 1000}$	Mean LST for an area corresponding to the area of Sentinel – 3 (LANDSAT)
$\varepsilon_{landsat,30}$	Emissivity for an image of high spatial resolution (LANDSAT)
$\varepsilon_{landsat,30 \to 1000}$	Mean emissivity for an area corresponding to the area of Sentinel 3

Part VI: UHI Mitigation

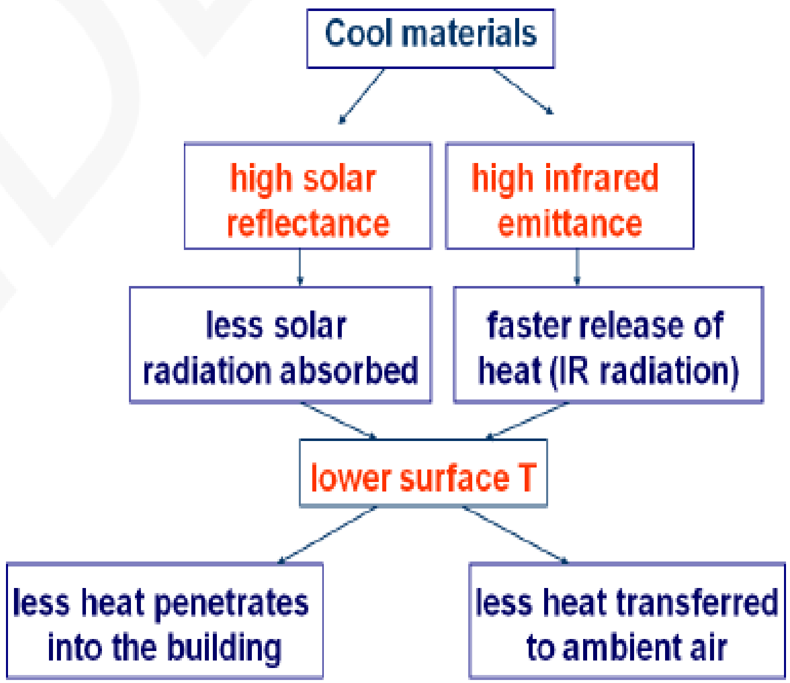
Source: Santamouris, 2014; Santamouris and Cartalis, 2015

UHI mitigation techniques

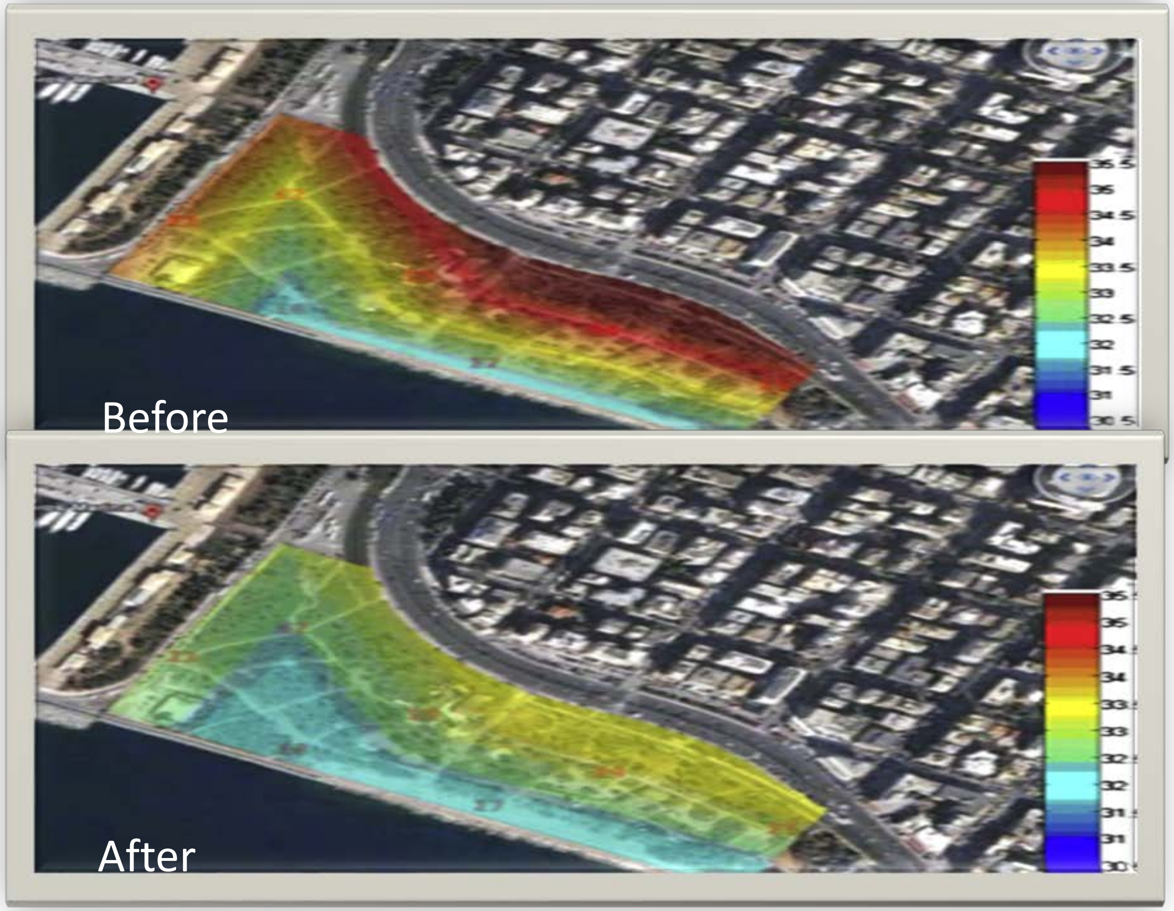
Methods	Applications examples
Creation of cool surfaces	Use of appropriate materials
	Green areas
	Water surfaces
	Creation of shading area
Reduction of anthropogenic heat	Energy conservation measures
	Heat release measures
Improvement of the urban environment	City block configuration
	Building configuration

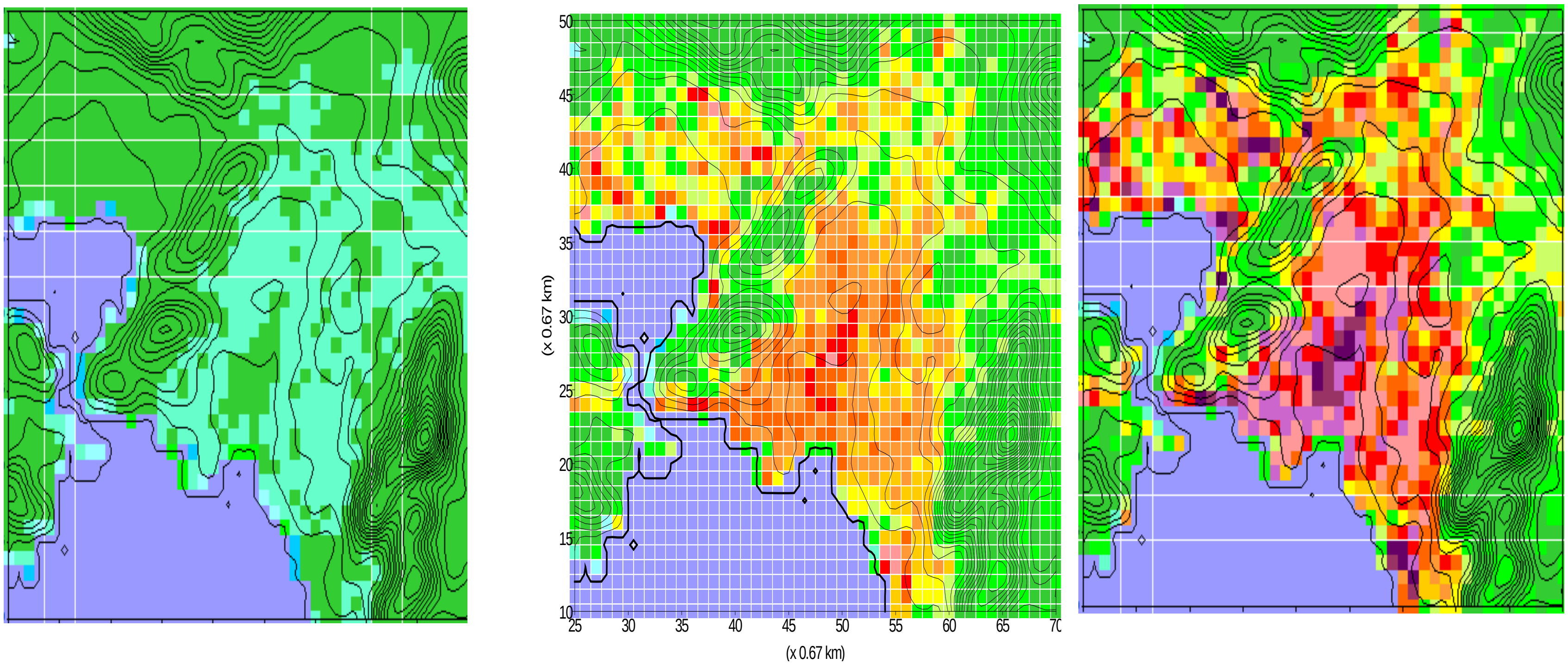
▸ Pavements and roofs comprise over 60% of urban surfaces. Vegetation cover presents a low percentage

Cool materials



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