Advanced thermal remote sensing

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ESA–MOST China Dragon 4 Cooperation

2019 ADVANCED INTERNATIONAL TRAINING COURSE IN LAND REMOTE SENSING

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培训时间:2019年11月18日-23日 主办方:重庆大学

Learning Objectives

What is thermal remote sensing?

Which are the laws describing thermal remote sensing?

What is the difference between kinetic temperature and radiant temperature?

What is emissivity and why is it relevant to thermal remote sensing?

How is land surface temperature influenced by the thermal properties of materials?

How to interpret thermal images?

How is land surface temperature estimated?

Which applications can be supported?

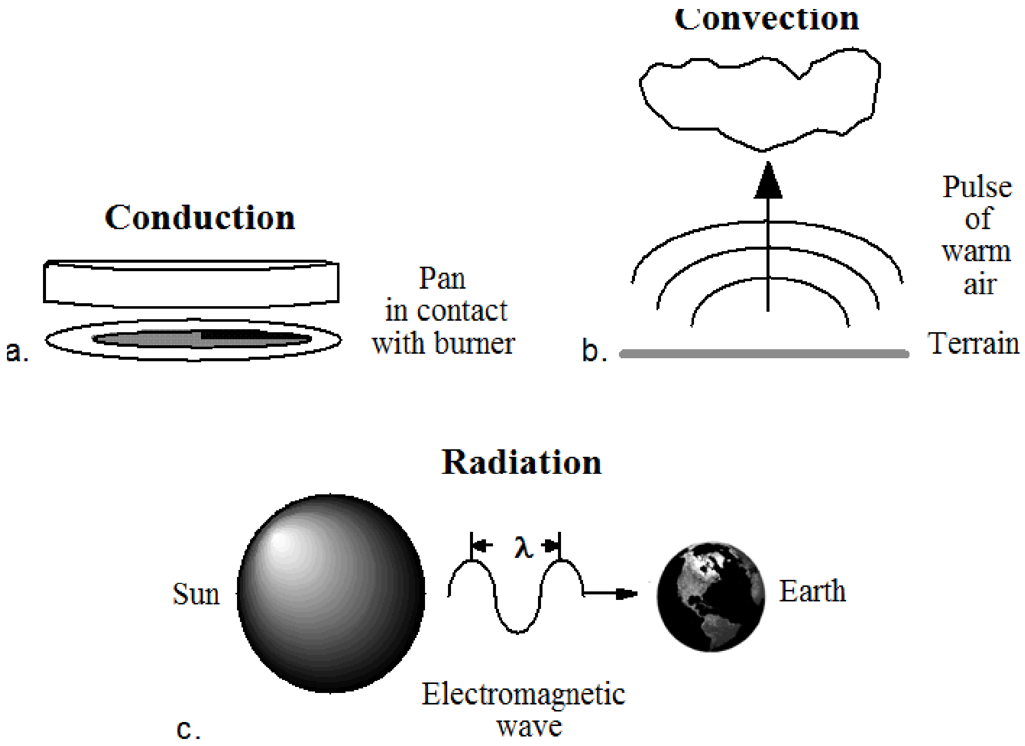
Introductory points -1

The three basic ways in which energy can be transferred:

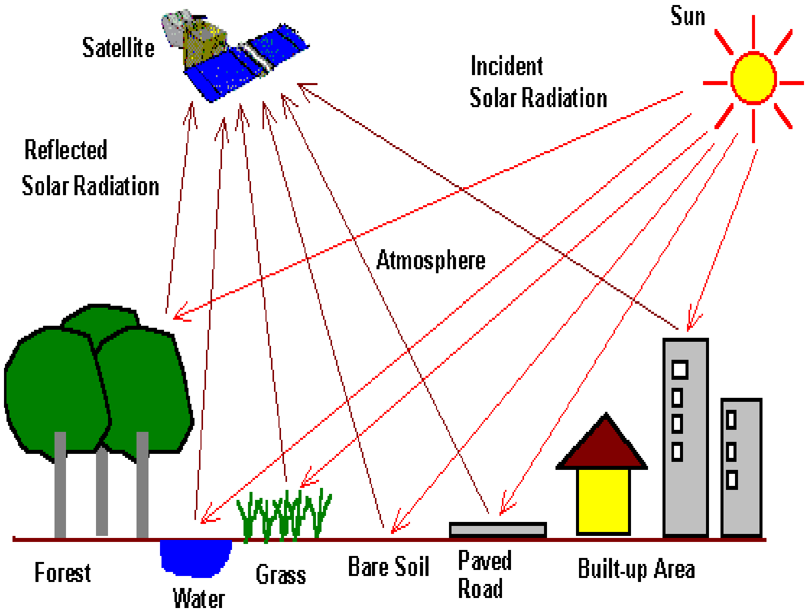
• ***Conduction*** occurs when one body (molecule or atom) transfers its kinetic energy to another by colliding with it. This is how a pan is heated on a stove.

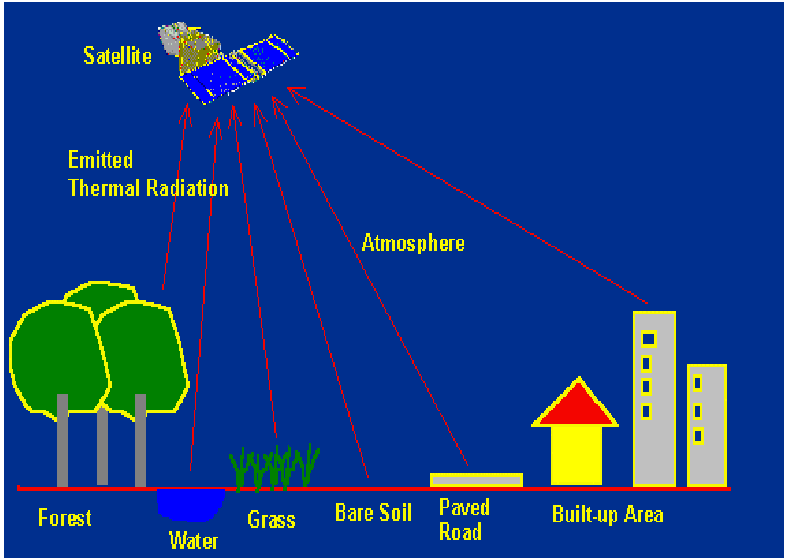
• **In *convection***, the kinetic energy of bodies is transferred from one place to another by physically moving the bodies. An example is the convectional heating of air in the atmosphere in the early afternoon.

• The transfer of energy by ***electromagnetic radiation*** is of primary interest to remote sensing because it is the only form of energy transfer that can take place in a vacuum such as the region between the Sun and the Earth.


Convection
Pulse
of
warm
air
Terrain
b.
Conduction
Pan
in contact
with burner
a.
Radiation
λ
Sun
Earth
Electromagnetic
wave
c.

Optical vs thermal remote sensing



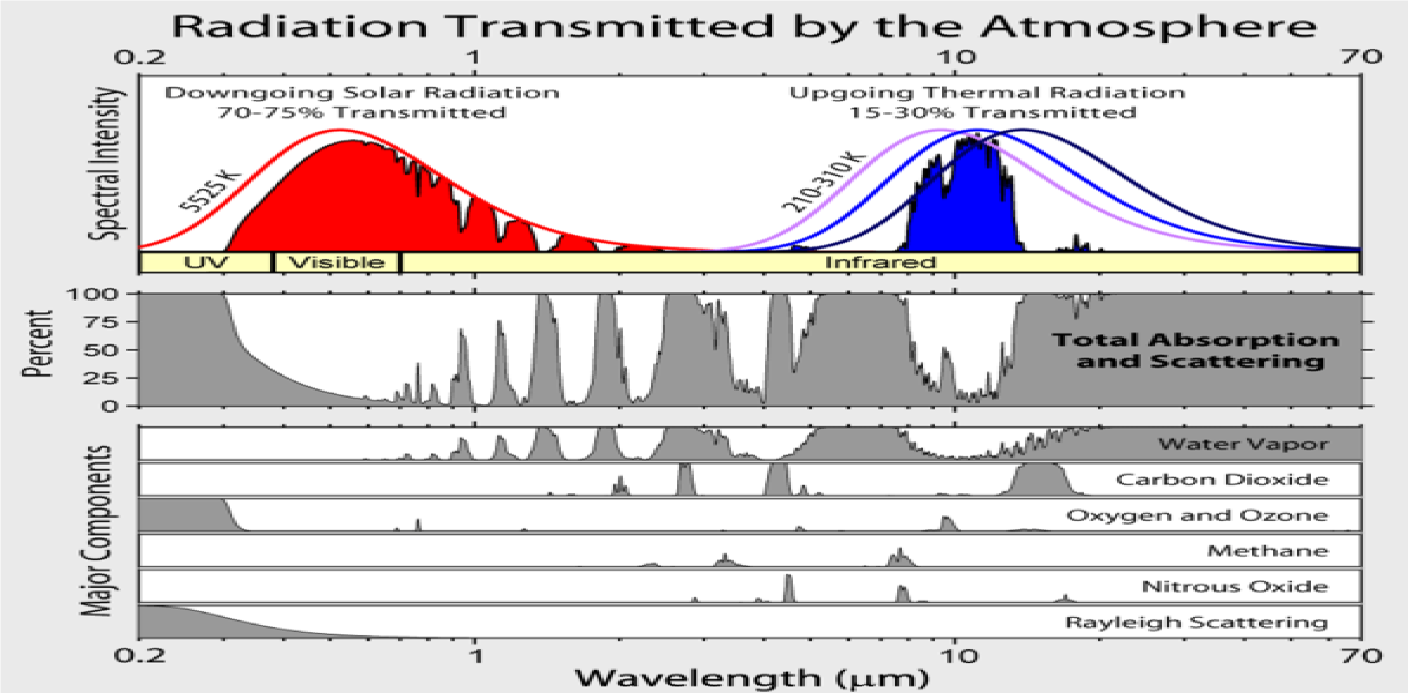


Introductory points - 2

The reason we can use remote sensing devices to detect infrared energy in these regions is because the atmosphere allows a portion of the infrared energy to be transmitted from the terrain to the detectors.

Regions that pass energy are called ***atmospheric windows***.

Regions that absorb most of the infrared energy are called ***absorption bands***. Water vapor (H_2O), carbon dioxide (CO_2), and ozone (O_3) are responsible for most of the absorption.



Spectal signature = f (λ)

Introductory points - 3

An object's **internal kinetic heat** is converted to **radiant energy** (often called external or apparent energy).

The electromagnetic radiation exiting an object is called ***radiant flux*** and is measured in watts. The concentration of the amount of radiant flux exiting (emitted from) an object relates to its radiant temperature (T_{rad}).

• There is usually a high positive correlation between the true kinetic temperature of an object (T_{kin}) and the amount of radiant flux radiated from the object (T_{rad}).

This is the basis of thermal infrared remote sensing.

Yet, the correlation (and the resulting relationship) is not perfect, with the remote measurement of the radiant temperature always being **slightly less** than the true kinetic temperature of the object.

This is due to a thermal property called emissivity which depends on the type of the radiating body and the wavelength.

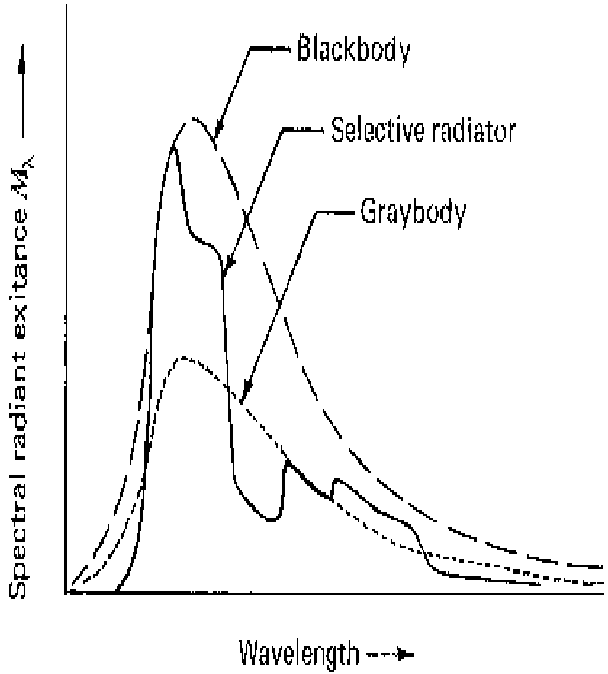
Emissivity, ε, is the ratio between the radiant flux exiting a real-world selective radiating body (F_r) and a blackbody at the same temperature (F_b).

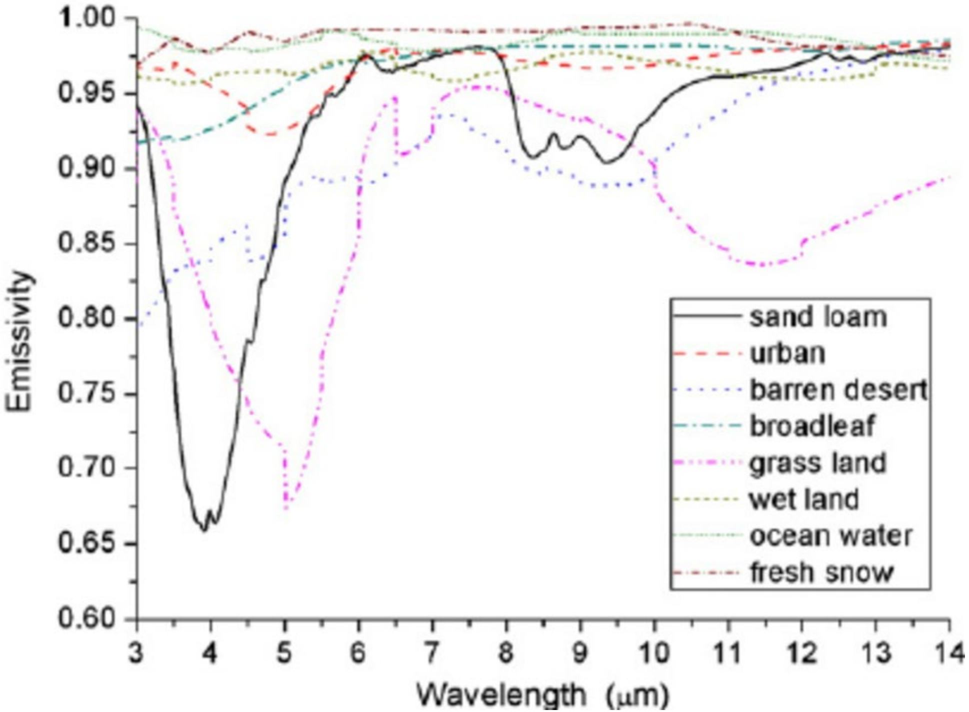
Radiation of real Materials

Emissivity depends on wavelength, surface temperature, and some physical properties of the surface, e.g. water content, or density.

Material	Average Emissivity over 8-14 μm
Clear water	0.98 - 0.99
Healthy green vegetation	0.96 - 0.99
Dry vegetation	0.88 - 0.94
Asphaltic concrete	0.94 - 0.97
Basaltic rock	0.92 - 0.96
Granitic rock	0.83 - 0.87
Dry mineral soil	0.92 - 0.96
Polished metals	0.06 - 0.21

Source: Lillesand et al. (2008)

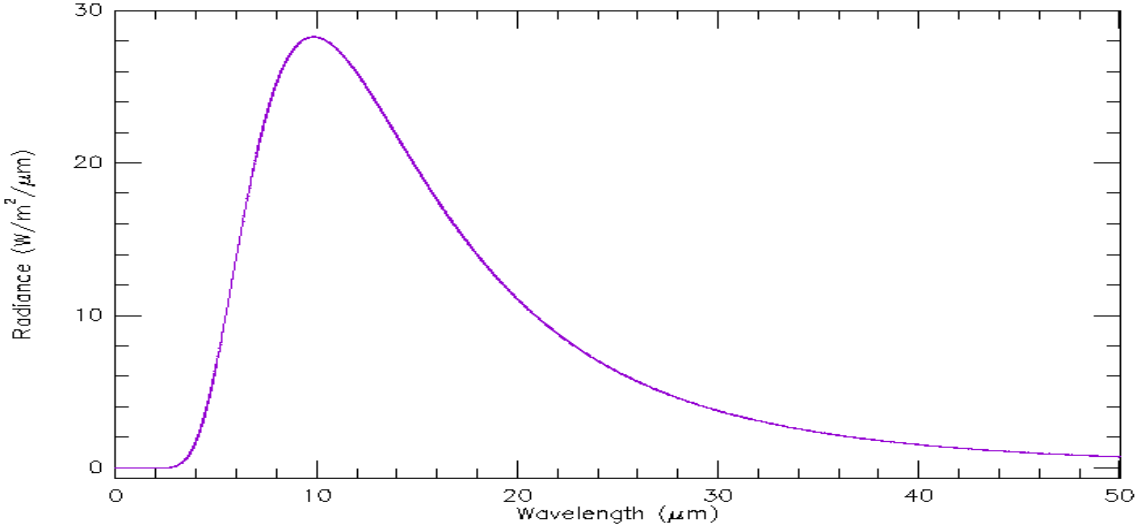




Source: Tang and Li, 2008
Remote Sensing of Environment

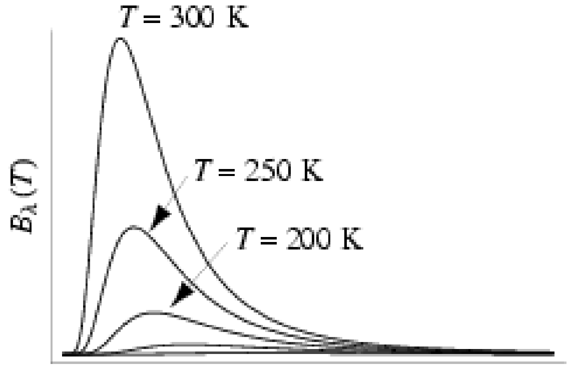
Planck blackbody equation:

describes the EM radiation emitted from a blackbody at a certain wavelength as a function of its absolute temperature



The distribution of energy from a blackbody at 70°F.

$$B(\lambda,T)=\frac{2\pi hc^2}{\lambda^5\left(e^{hc/(\lambda kT)}-1\right)}$$



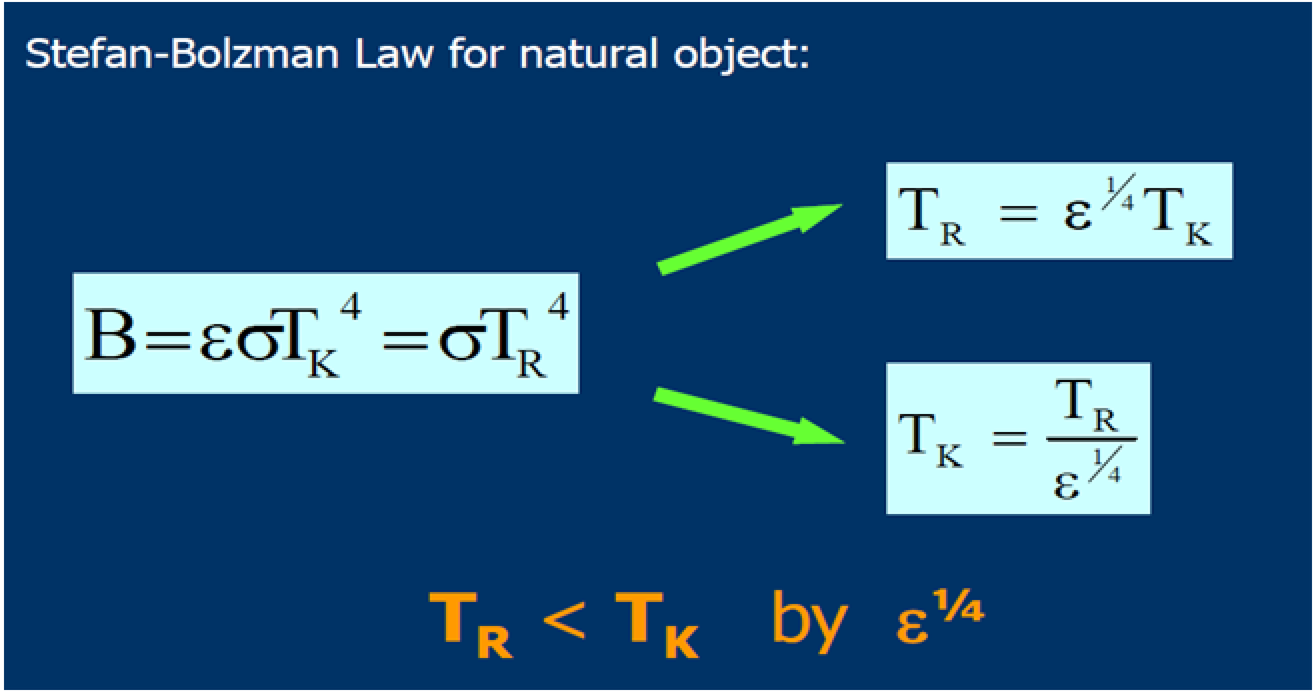
http://tes.asu.edu/MARS_SURVEYOR/MGSTES/TES_emissivity.html

Planck equation for blackbody radiance

$$B_\lambda = \frac{2\pi hc^2}{\lambda^5 (e^{\frac{hc}{k\lambda T}} - 1)}$$

→ radiance temperature $T_R = T_B$
(brightness temperature)

$$T_B = \frac{K_2}{\ln\left(\frac{K_1}{B_\lambda} + 1\right)}$$



T_K the kinetic temperature

Kirchhoff's radiation law

According to Kirchoff's radiation law for a blackbody: $\alpha_\lambda = \varepsilon_\lambda$

Thus $1 = r_\lambda + \alpha_\lambda + \tau_\lambda$ can be written as $1 = r_\lambda + \varepsilon_\lambda + \tau_\lambda$

where r_λ is spectral hemispherical reflectance by the terrain,

α_λ is spectral hemispherical absorptance, and

τ_λ is spectral hemispherical transmittance

But most real-world materials are usually opaque to thermal radiation meaning that no radiant flux exits from the other side of the terrain element. Therefore, we may assume transmittance, $\tau_\lambda = 0$

Thus: $1 = r_\lambda + \varepsilon_\lambda$

which implies that the higher an object's reflectance in the thermal infrared region, the lower the emissivity and vice versa.

Important note for thermal analysis

Two materials on the ground could have **the same true kinetic temperature but have different apparent temperatures** when sensed by a thermal radiometer simply because their emissivities are different.

The emissivity of an object may be influenced by a number factors, including:

• <u>color</u> - darker colored objects are usually better absorbers and emitters (i.e. they have a higher emissivity) than lighter colored objects which tend to reflect more of the incident energy.

• <u>surface roughness</u> - the greater the surface roughness of an object relative to the size of the incident wavelength, the greater the surface area of the object and potential for absorption and re-emission of energy.

- moisture content - the more moisture an object contains, the greater its ability to absorb energy and become a good emitter. Wet soil particles have a high emissivity similar to water.

- compaction - the degree of soil compaction can effect emissivity.

- field-of-view/resolution - the emissivity of a single leaf measured with a very high resolution thermal radiometer will have a different emissivity than an entire tree crown viewed using a coarse spatial resolution radiometer.

- wavelength - the emissivity of an object is generally considered to be wavelength dependent. It may be constant in one spectral interval, but varying in another (*see Spectral Signature*)

- viewing angle - the emissivity of an object can vary with sensor viewing angle.

Estimating LST

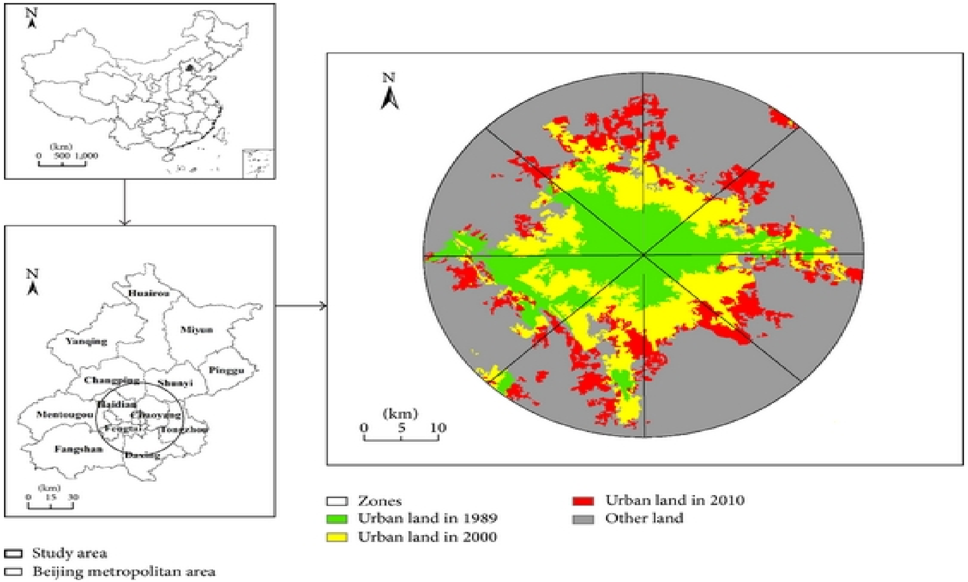
Step 1. Develop a data base for your city

Climate data for Beijing (normals 1971–2000, extremes 1961–2000) [hide]

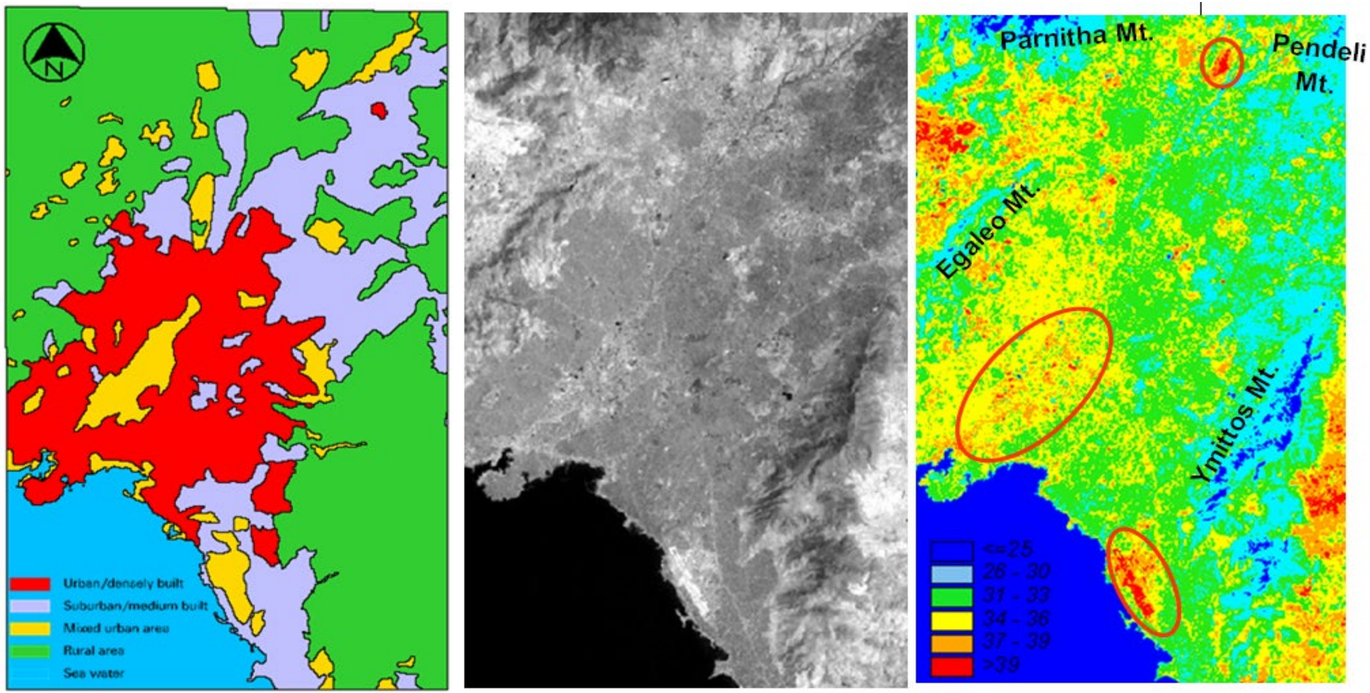
Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Record high °C (°F)	14.3 (57.7)	19.8 (67.6)	29.5 (85.1)	33.0 (91.4)	38.3 (100.9)	42.6 (108.7)	41.9 (107.4)	38.3 (100.9)	35.0 (95)	31.0 (87.8)	23.3 (73.9)	19.5 (67.1)	42.6 (108.7)
Average high °C (°F)	1.8 (35.2)	5.0 (41)	11.6 (52.9)	20.3 (68.5)	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)



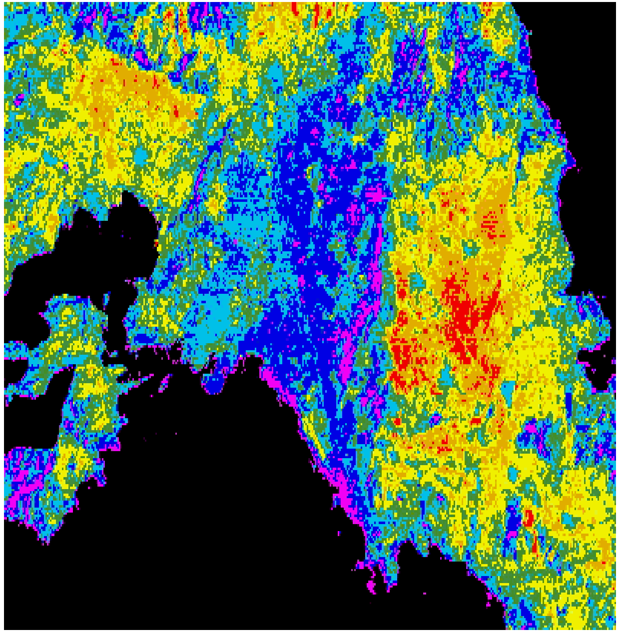
The spatial distribution of urban land in Beijing during 1989–2010.



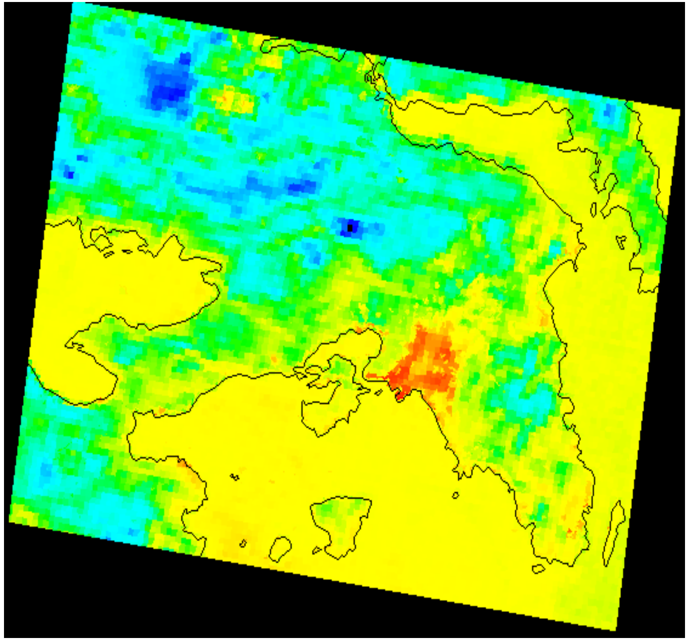
Left to right: Land cover, satellite image in the visible, thermal image

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

120m resolution

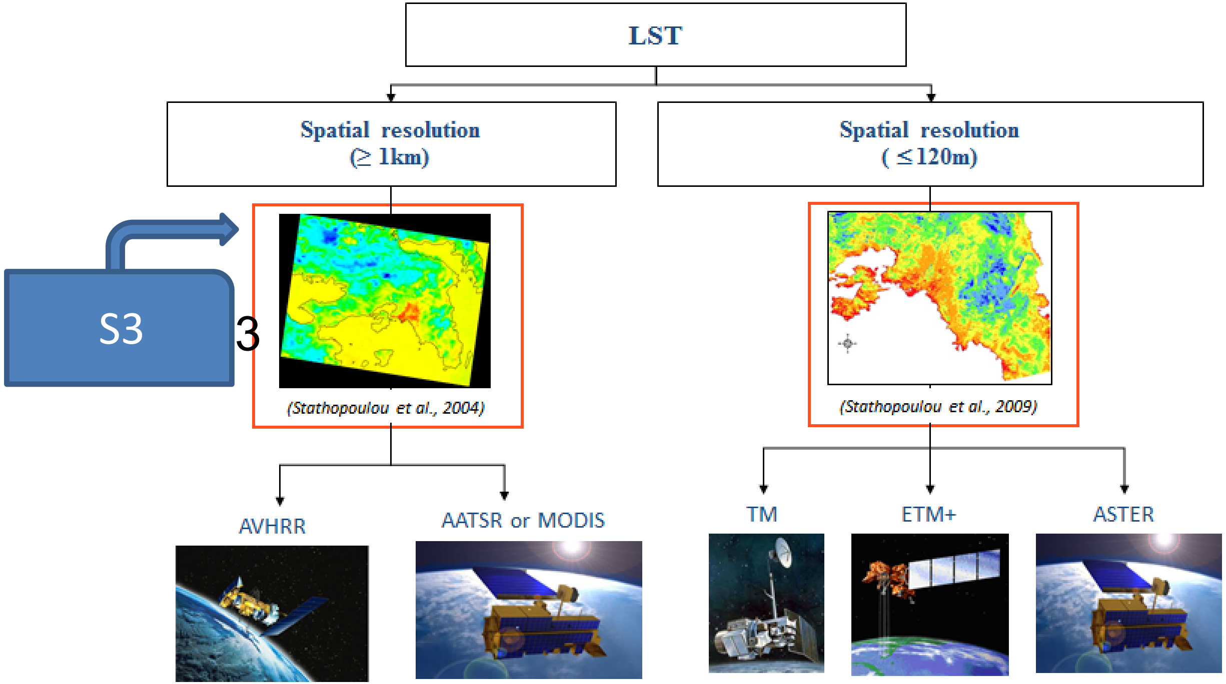


1 km resolution

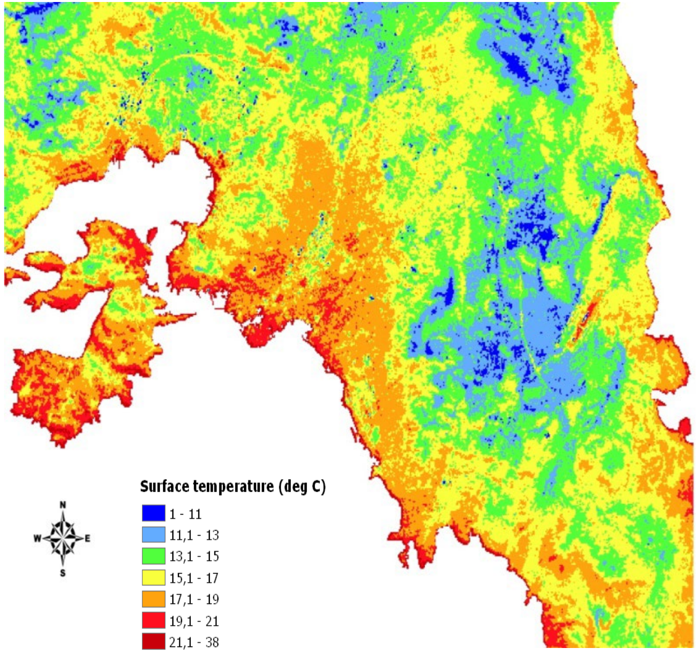


Source: processing by C.Cartalis

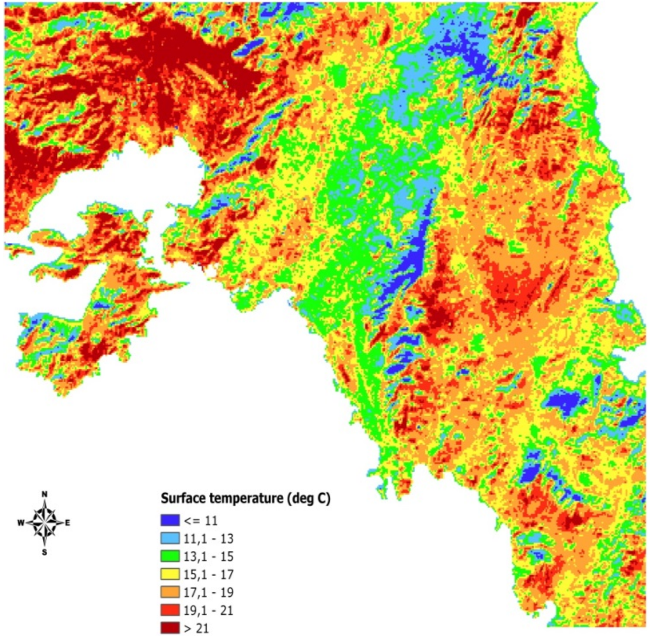
Step 4. Choose the right satellite mission – Merge satellite data



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



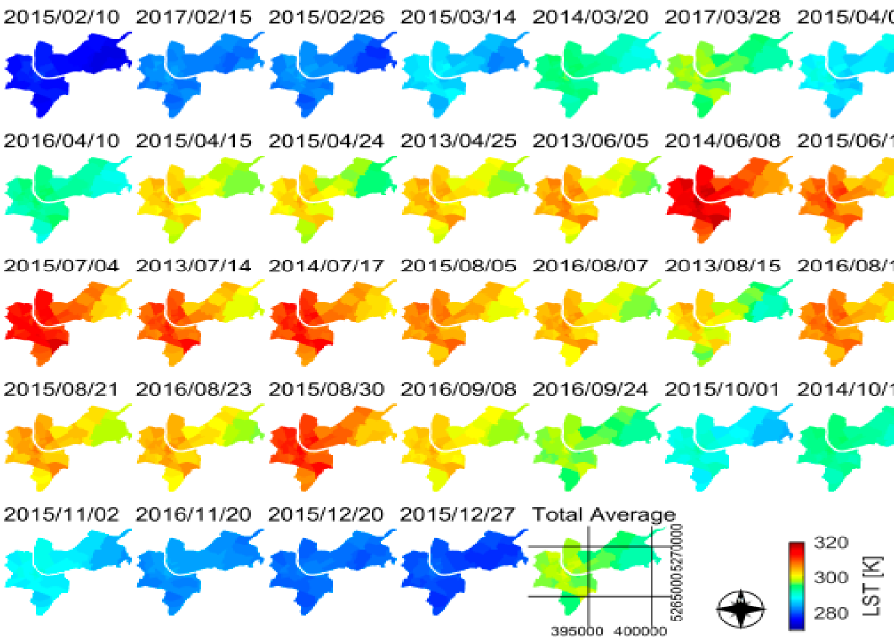
22:32 local time



10:30 local time

Source: processing by C. Cartalis

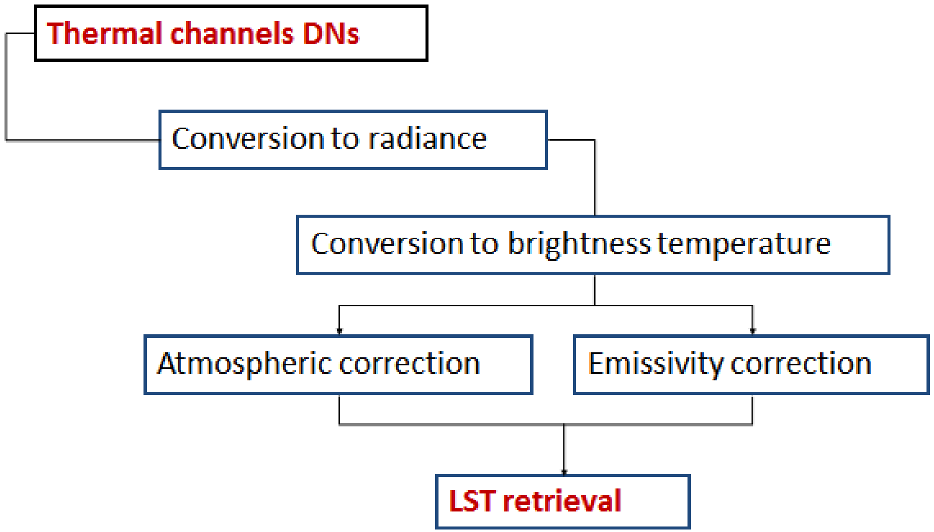
Step 6. Which period of the year?



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



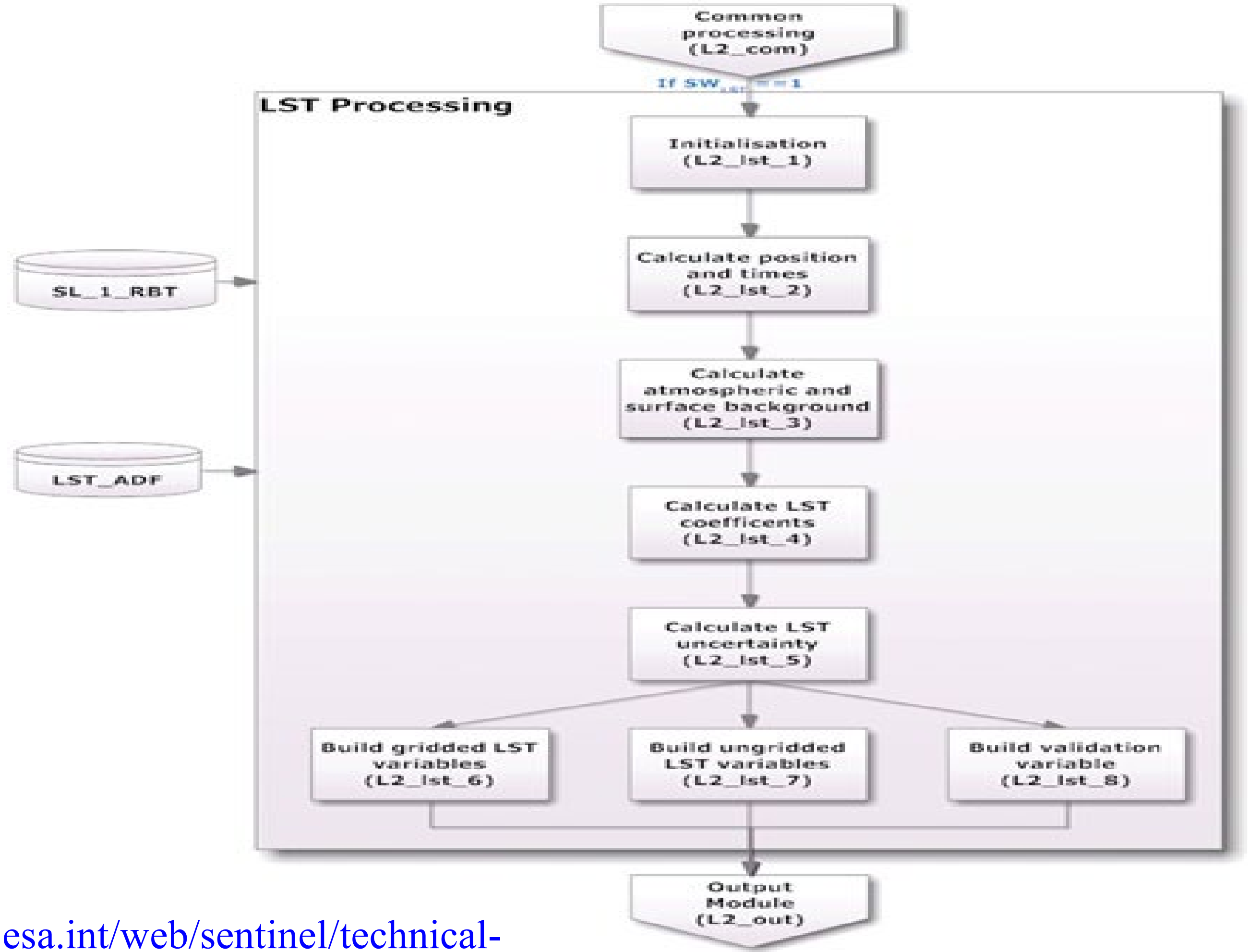
Overall LST accuracy: ±2 Kelvin

Sentinel -3 Sea and Land Surface Temperature Radiometer (SLSTR)

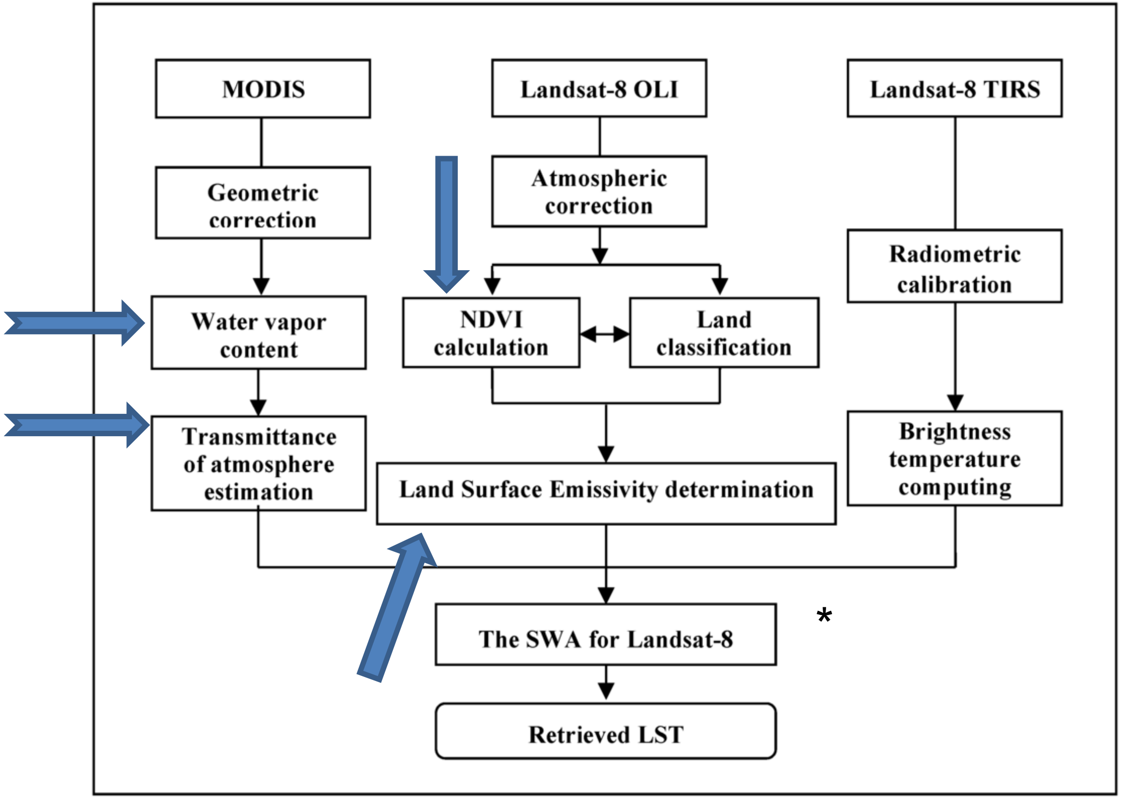
The Land Surface Temperature (LST) processing includes a split-window method, using radiances from two channels, the band centres of which are close in wavelength, to determine the effective radiometric temperature of the Earth's surface "skin" in the instrument field of view. This method assumes that the linearity of the relationship between LST and BT results from linearisation of the Planck function and linearity of the variation of atmospheric transmittance with column water vapor amount. The algorithm is:

$$LST = a_0 + b_0 T_{11} + c_0 T_{12}$$

where a_0, b_0 and c_0 are classes of coefficients that depend on atmospheric water vapour, satellite viewing angle and land surface emissivity. T_{11} and T_{12} represent the brightness temperatures measured at 11 µm and 12 µm respectively.



https://sentinel.esa.int/web/sentinel/technical-guides/sentinel-3-slstr/level-2/lst-processing



*split window algorithm

Land Surface Temperature from Landsat TM images

1. Converting the digital number of Landsat TM or ETM+ TIR band into spectral radiance Radiance = 0.0370588 × DN + 3.20 (For Landsat7 ETM+) Radiance = 0.0553760 × DN + 1.18 (For Landsat5 TM)

2. Converting the **spectral radiance to at satellite brightness temperature** (i.e., blackbody temperature, TB) TB = K2/[ln(K1/Radiance + 1)] *Where "ln" is Natural Logarithm, and K2 and K1 are pre-launch calibration constants (For Landsat7 ETM+, K2=1282.71 K, and K1=666.09 W/(m2 sr um)) (For Landsat5 TM, K2=1260.56 K, and K1=607.76 W/(m2 sr um))*

3. Converting the **blackbody temperature to land surface temperature (LST)** which involves correcting for spectral emissivity according to the nature of land cover.

LST = TB /[(1 + (λ × TB / ρ)×ln(ε)] where: k = wavelength of emitted radiance (λ = 11.5 um), ρ = h×c/σ = 1.438×10-2 m K, σ = Boltzmann constant (1.38×10-23 J/K), h = Planck's constant (6.626×10-34 J s), and c = velocity of light (2.998×108 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 LW bands i and j (in Kelvin)

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

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

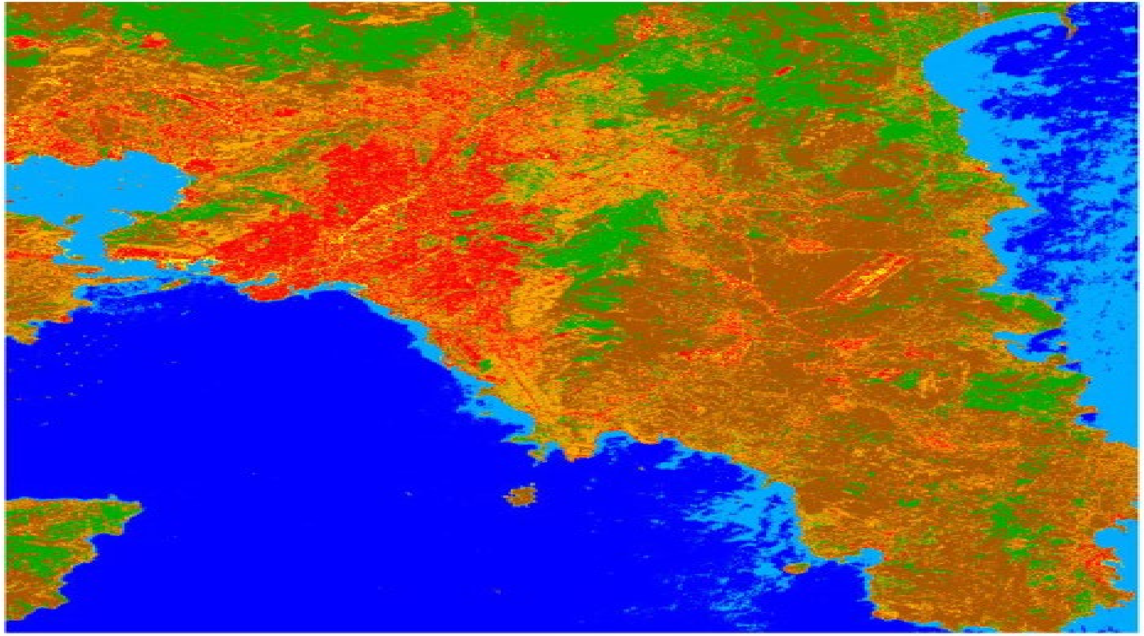
W is the total atmospheric water vapor content (in grams per square centimeter),

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.

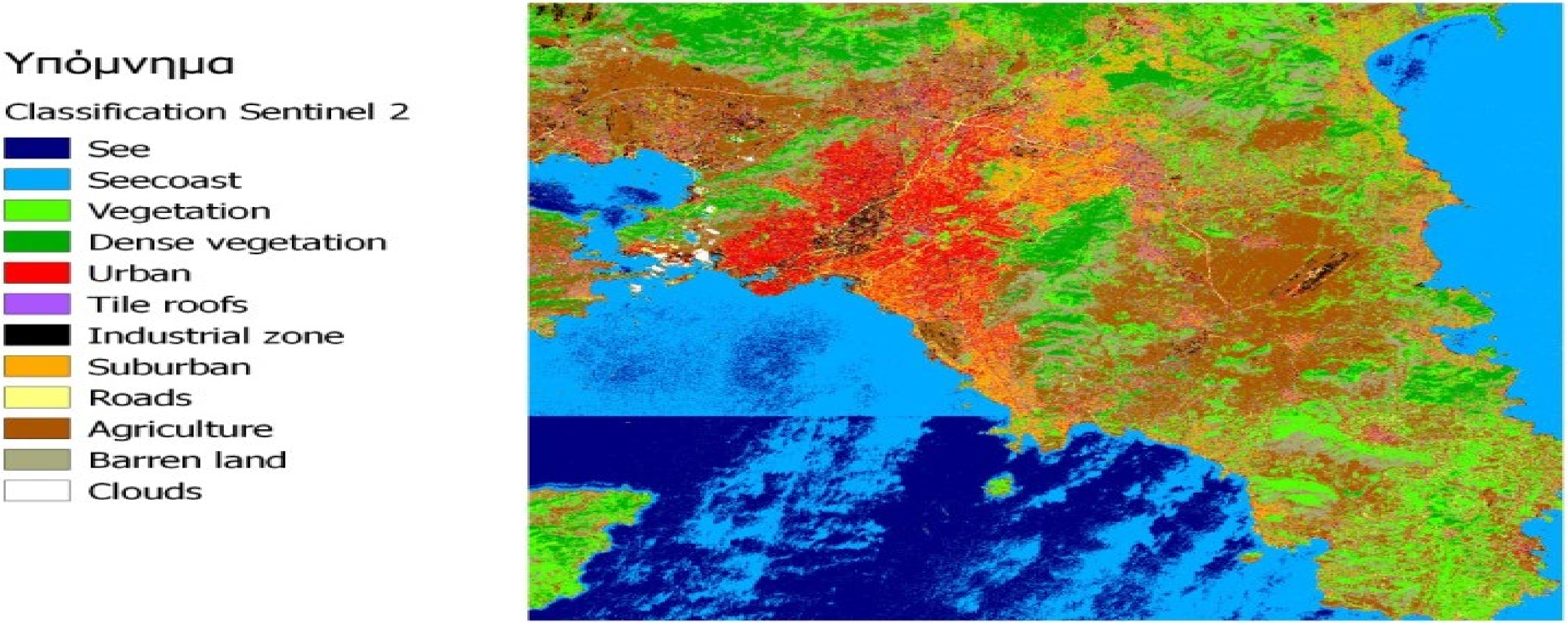
Assessing the thermal environment in urban areas with the use of land cover and land surface emissivity data of varying spatial resolutions

CLASSIFICATION LANDSAT – 8 IMAGE



Source for Slides 71-79, Remote Sensing and Image Processing Unit ,Univ. of Athens, 2017 (G. Giannakogiorgos)

CLASSIFICATION SENTINEL -2 IMAGE



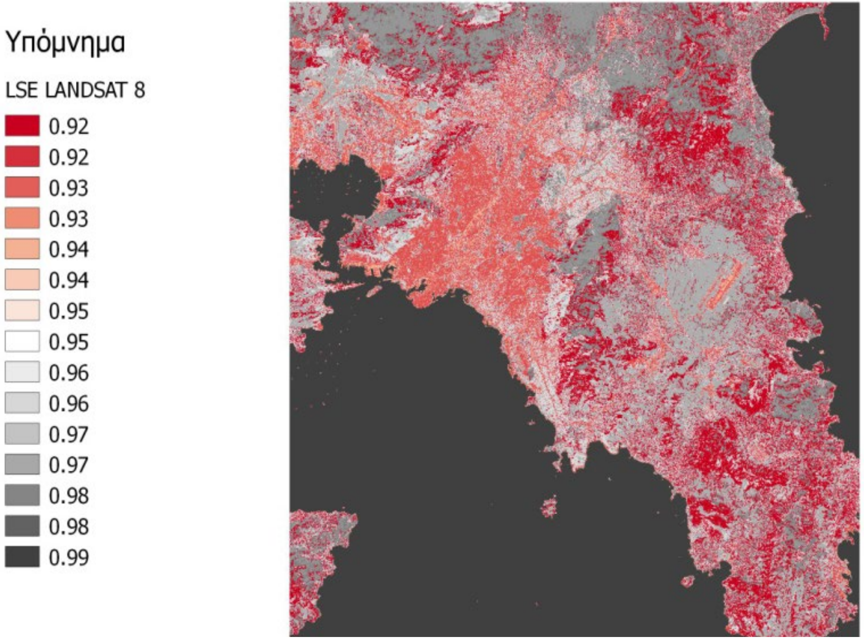
ACCURACY ASSESSMENT

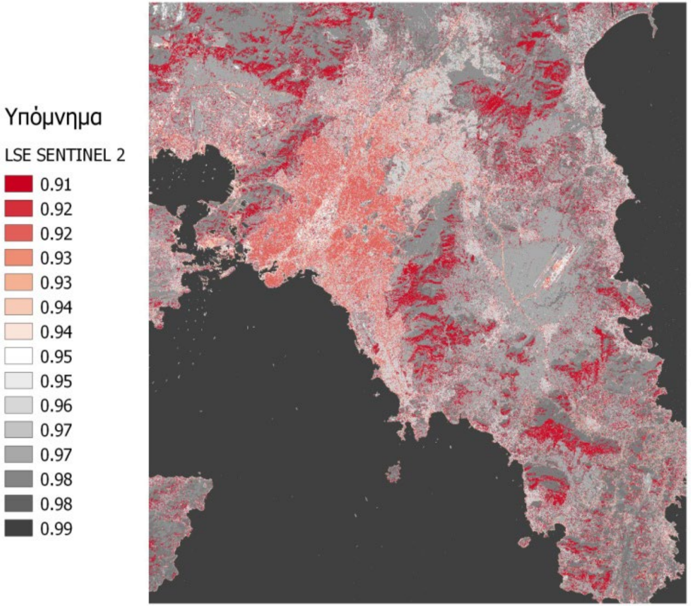
Accuracy = (sum of elements of principal diagonal / total number)

Landsat - 8 68.73%

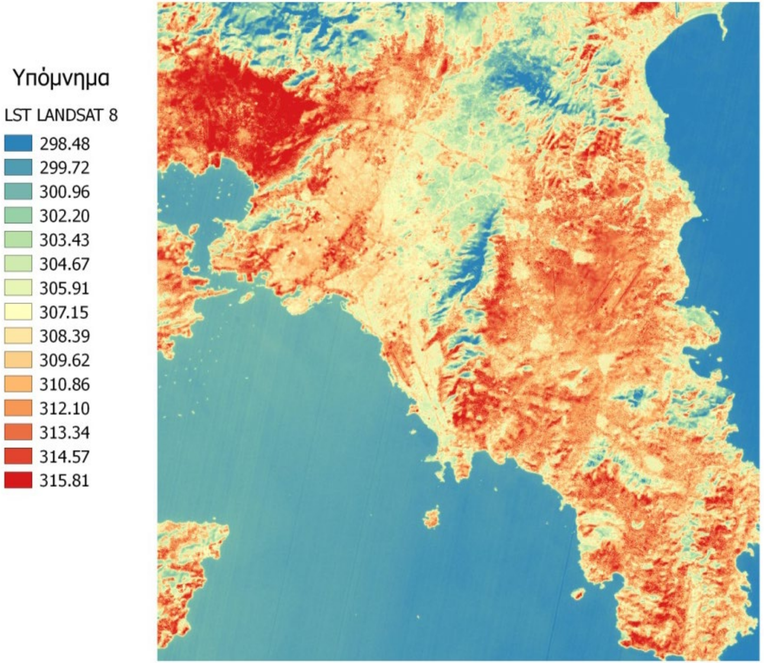
Sentinel -2 73.82%

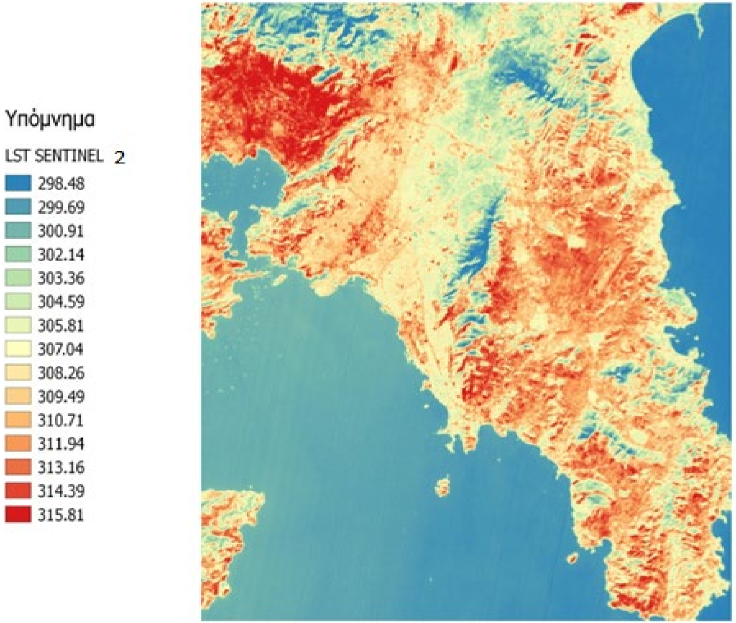
ASSESSMENT OF EMISSIVITY ON THE BASIS OF LANDSAT -8 (left) and SENTINEL -2 (right) LAND COVER CLASSIFICATION





LST as estimated with the use of land cover deduced from LANDSAT – 8 (left) AND SENTINEL – 2 (right)





COMPARISON OF AIR TEMPERATURE AS EXTRACTED FROM LST

($Ta = 1.2104Ts - 17.676$)

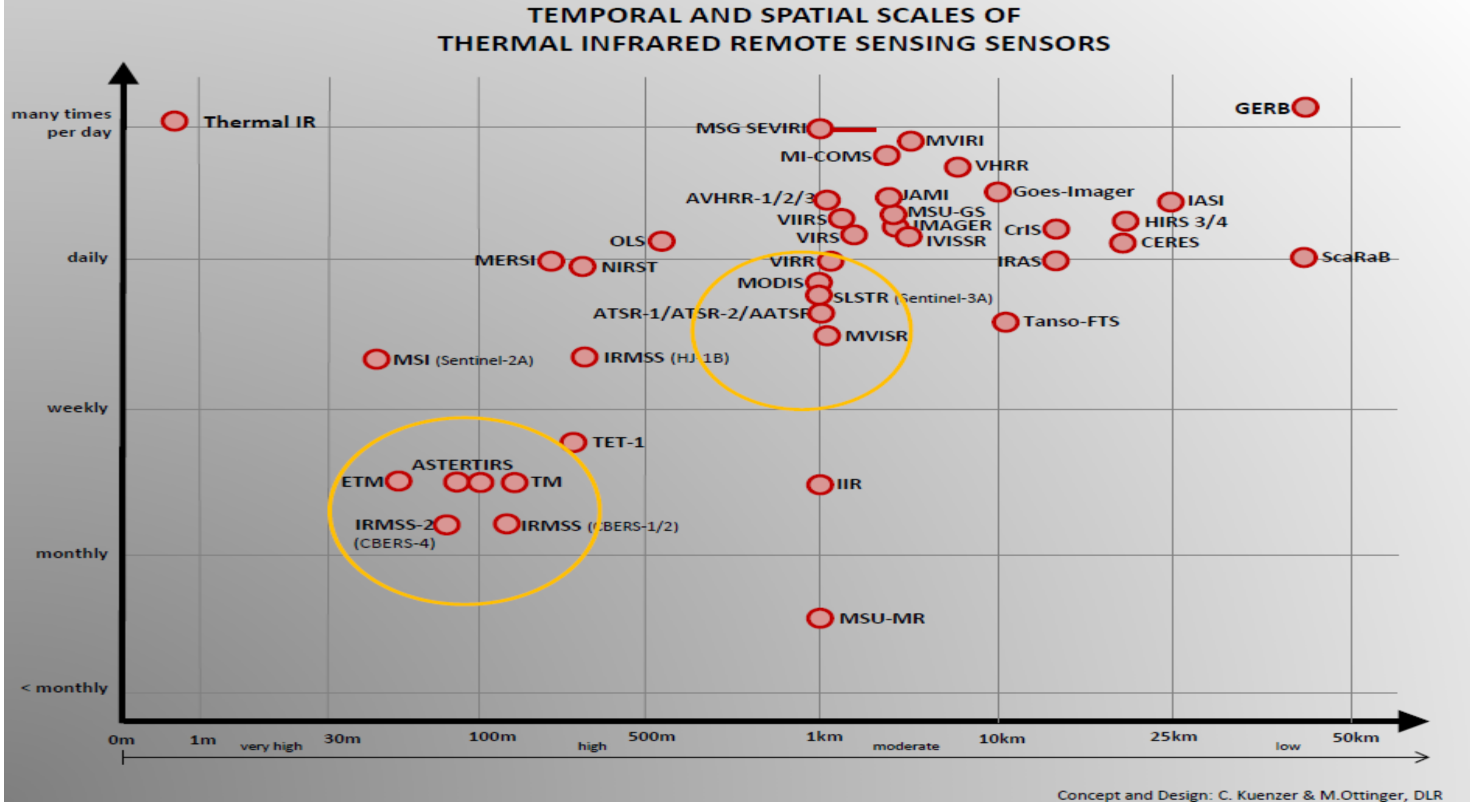
(Stathopoulou and Cartalis, 2005)

STATIONS	$T_{air\ data}$(C)	$T_{air\ Sentinel}$(C)	$T_{airdata}$-T_{Sent}C)	$T_{air\ Landsat}$(C)	$T_{airdata}$-$T_{Landsat}$(C)
1	25,3	24,6	0,7	26,1	-0,8
2	24,4	24,6	-0,2	24,7	-0,3
3	25	24,5	0,5	24,4	0,6
4	25,7	25,2	0,5	24,6	1,1
5	25	24,6	0,4	26,5	-1,5
6	22,7	21,2	1,5	19,9	2,8
7	24,4	24,7	-0,3	25,4	-1
8	24,3	24,4	-0,1	25,4	-1,1
9	24,9	23,9	1	23,9	1
10	25,2	24,8	0,4	24,5	0,7
11	23,8	23,5	0,3	25,2	-1,4
12	24,2	25,1	-0,9	25,6	-1,4

- 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

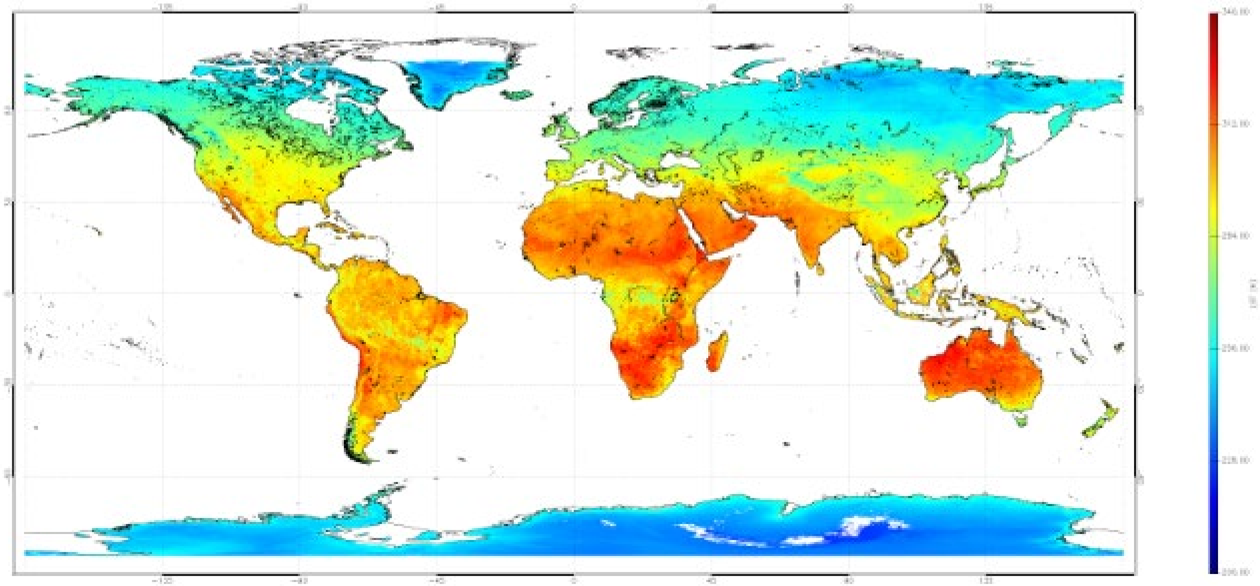
The critical balance between spatial and temporal resolution

Temporal to spatial resolution – a delicate (and critical) balance



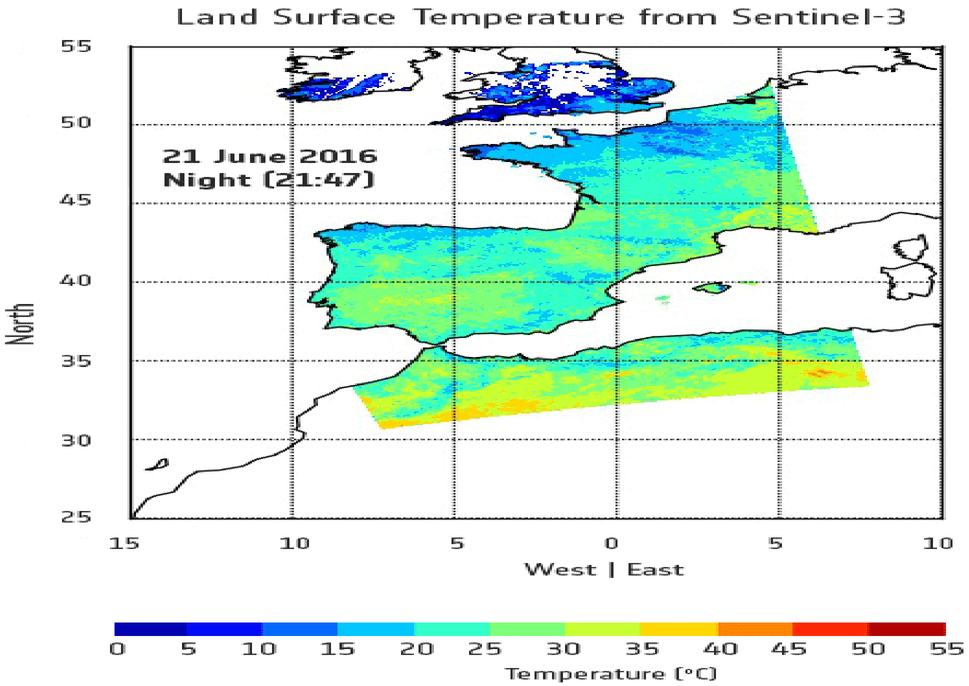
APPLICATIONS OF THERMAL REMOTE SENSING

Climate Dynamics



Information from Sentinel-3A's radiometer, which measures radiation emitted from Earth's surface, reveal how the temperature of Earth's land changes between July and November 2016. Measurements are in Kelvin.

Land surface temperature dynamics

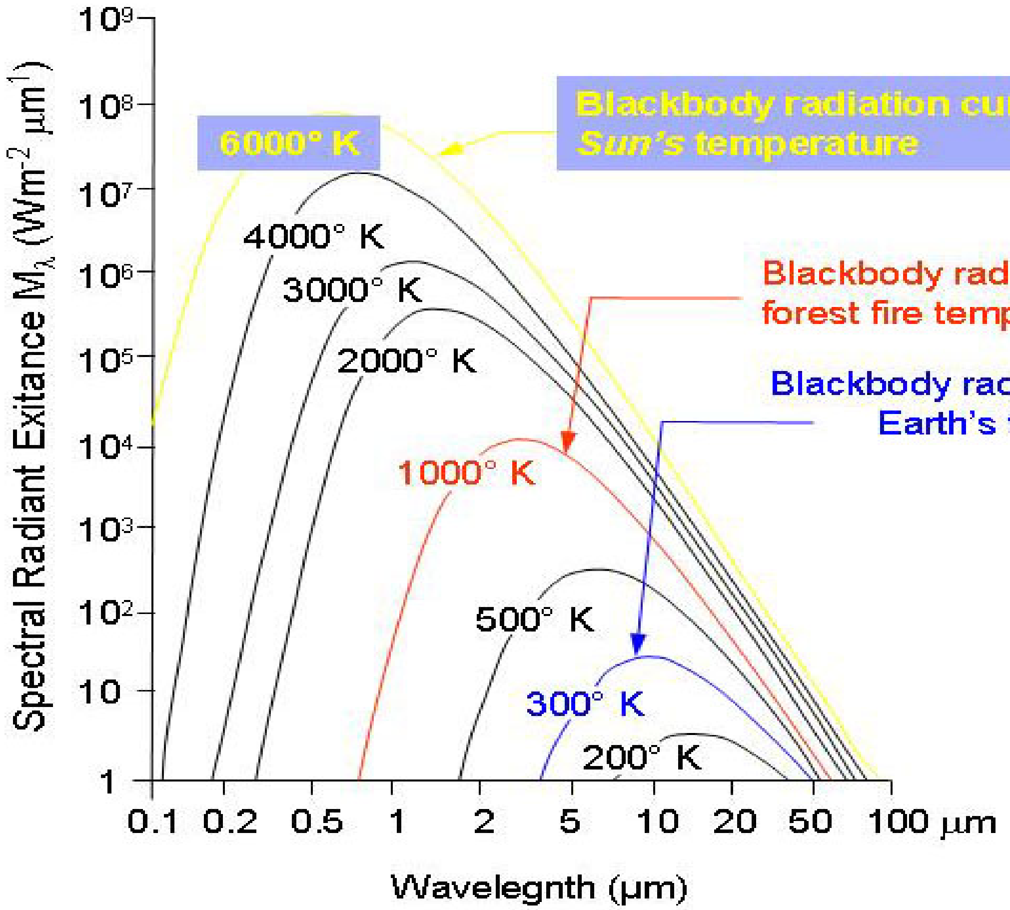


Remote sensing and forest fires

Remote sensing can contribute to the three phases of fire management:

Pre-fire: Fuel conditions and amount
Active fires: detection and fire properties **(THERMAL)**
Post-fire: burned area, severity and emissions

Active fires: the thermal signal is discrete**,** especially when using instruments that do not saturate at low temperature. Confusion may be introduced due to signals from oil refineries and volcanic eruptions.



Spectral Radiant Exitance M_λ ($Wm^{-2}\ \mu m^{-1}$)
10^9
10^8
10^7
10^6
10^5
10^4
10^3
10^2
10
1
0.1
0.2
0.5
1
2
5
10
20
50
100 μm
Wavelegnth (μm)
6000° K
4000° K
3000° K
2000° K
1000° K
500° K
300° K
200° K
Blackbody radiation curve at the *Sun's* temperature
Blackbody radiation curve at forest fire temperatures
Blackbody radiation curve at the Earth's temperature

•A fire at 500K will be sensed, as it grows

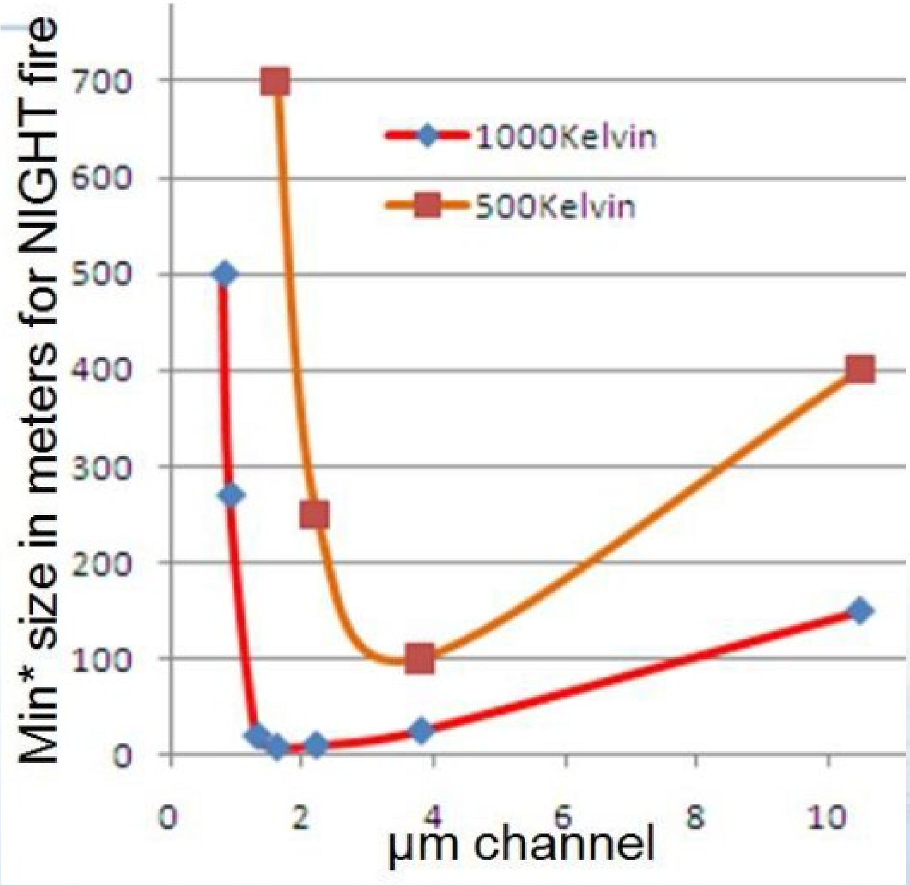
•first by 3.9µm(at ~100m)

•second by 2.2µm (250m)

•third by 10.8µm (400m)

•An RGB=(3.9;2.2;10.8) might be a good indicator for severity of a fire.

•For a hotter fire (1000K), typically gas flares, channels in the solar domain react faster than 3.9µm



Comparing window channels in the thermal infrared

Near infrared (1.6 µm)	More adequate for smoke detection than 3.9 µm Small fires not visible No CO_2 absorption (higher fire temperature) High sub pixel sensitivity
Middle infrared (3.9 µm)	High temperature sensitivity - major sub pixel effects (hot spots are easily detected) Negligible absorption by atmospheric humidity Close to a CO_2 absorption band, 4-7 Kelvin signal reduction Brightness is temperature of the CO_2 layer above the fire
Thermal infrared (10.8 µm)	1-2 Kelvin absorption by atmospheric humidity No signal reduction by CO_2 Lower temperature sensitivity (small subpixel effects) No risk of sensor blinding by fires Low values compared with 3.9 µm due to semi transparent cloud or smoke

Athens

Two days later … 26,000 m^2
of the forest were burned

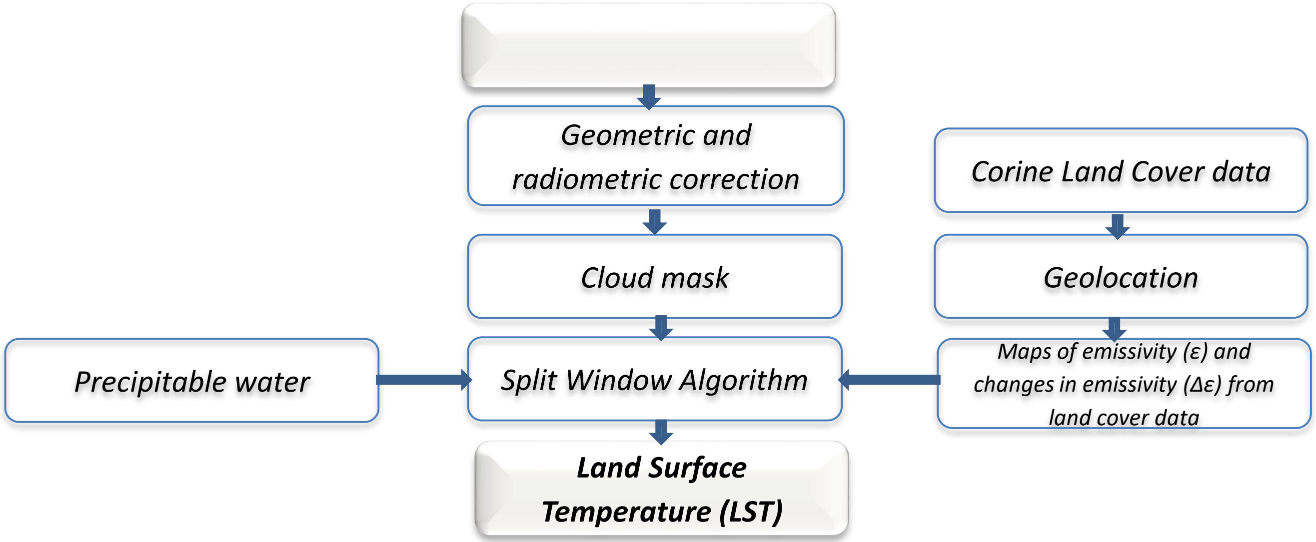
???
?

http://www.esa.int/var/esa/storage/images/esa_multimedia/images/2017/08/kalamos_fires/17122699-1-eng-GB/Kalamos_fires.gif

LAND SURFACE TEMPERATURE - Heat stress + long term TRENDS

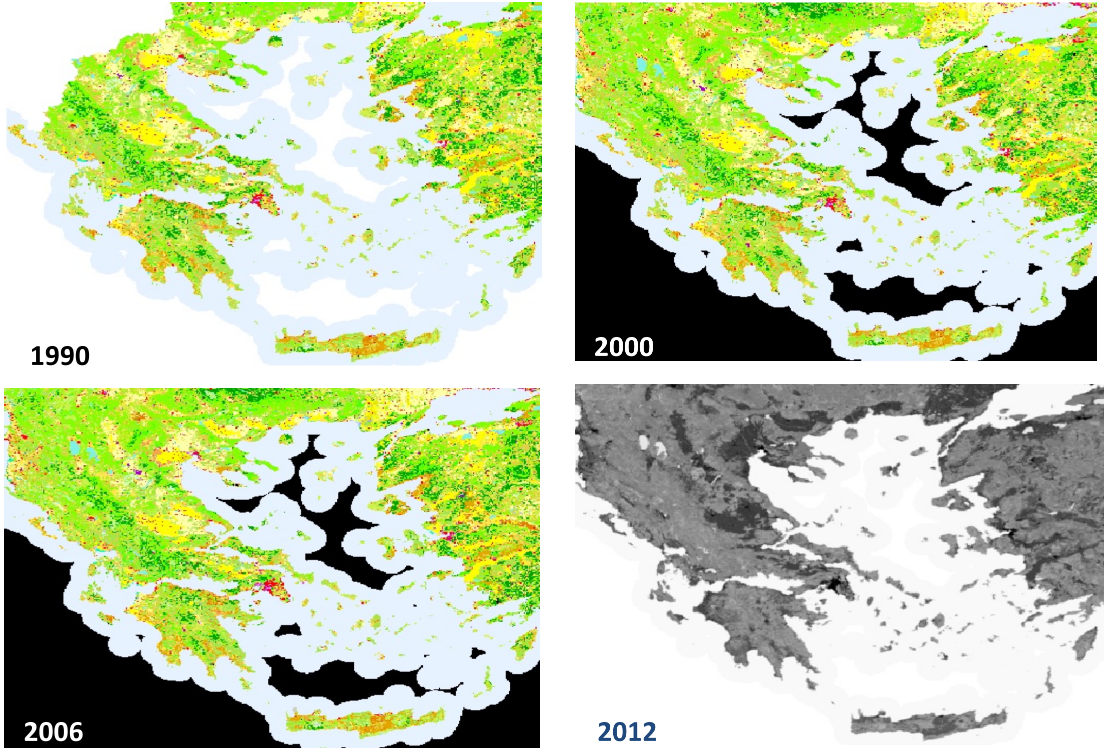
Slides 57-67,
Remote Sensing and Image Processing Unit,
University of Athens

Long term trends in LST for land surface dynamics



$$LSTtrend(\%) = \frac{LST(2015) - LST(1995)}{LST(1995)} 100$$

CORINE LAND COVER



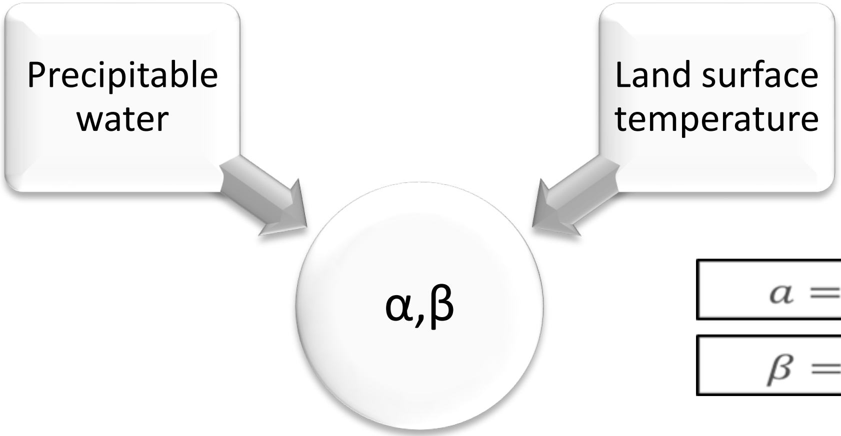
Extraction of ε and change of ε, depending on land cover

Area	Δε	E
Urban	-0.007	0.97
Semi-urban	-0.003	0.98
Rural	0	0.989

SPLIT WINDOW ALGORITHM

$$T = 0.51 + T_4 + (T_4 + T_5) + 0.58(T_4 - T_5)^2 + a(1-\varepsilon) - b\Delta\varepsilon$$

T_4 = brightness temperature channel 4
T_5 = brightness temperature channel 5
ε = mean spectral emissivity for channels 4 and 5

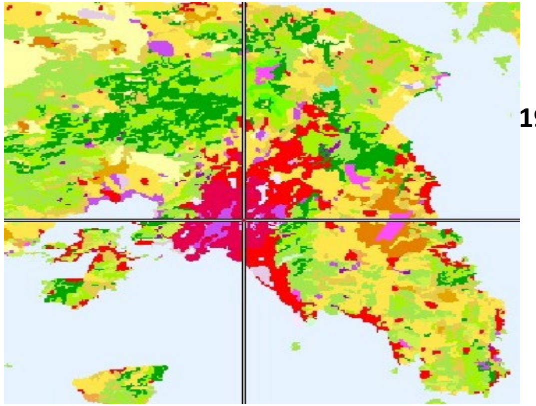


12:00 UTC	PW (gr/cm^2)
July	1.669

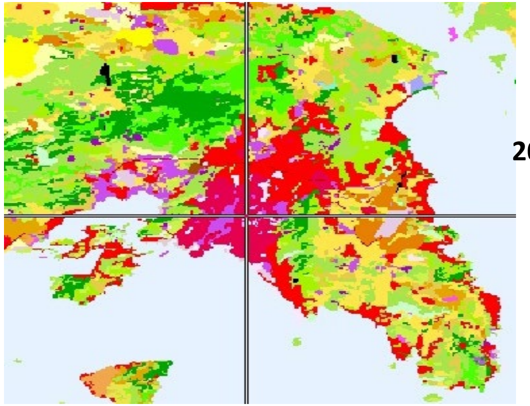
$$a = (0.190 \cdot PW - 0.103)T_4 - 67 \cdot PW + 107$$

$$\beta = (0.100 \cdot PW - 1.118)T_4 - 68 \cdot PW + 163$$

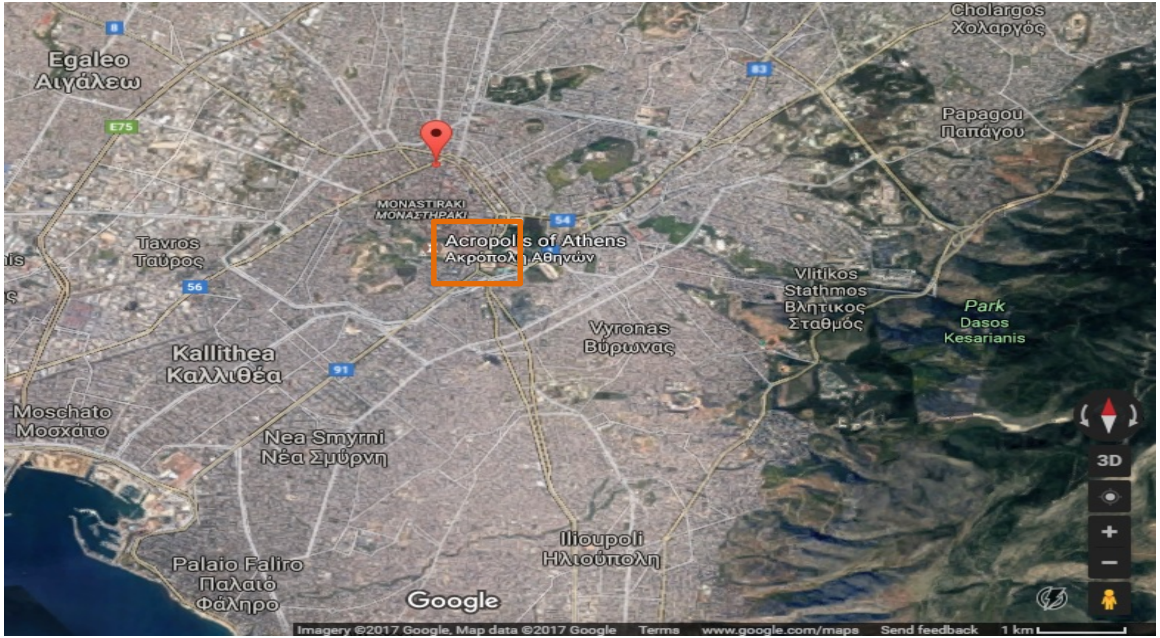
Center of Athens



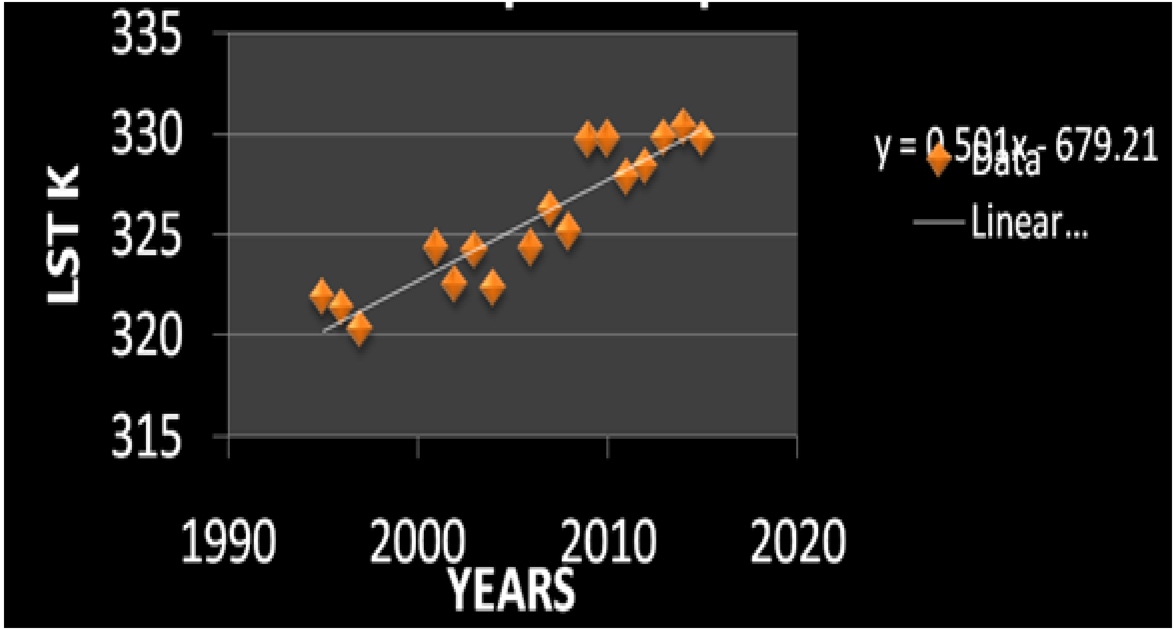
1990



2006

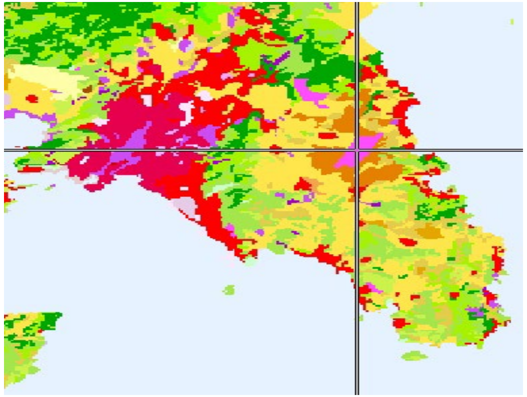


Center of Athens

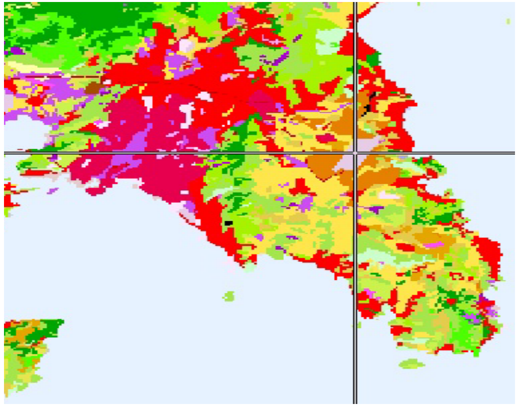


Mean value	325.763 K
Trend	3.1 %
Increase	10 K

Landscape change – from natural to built

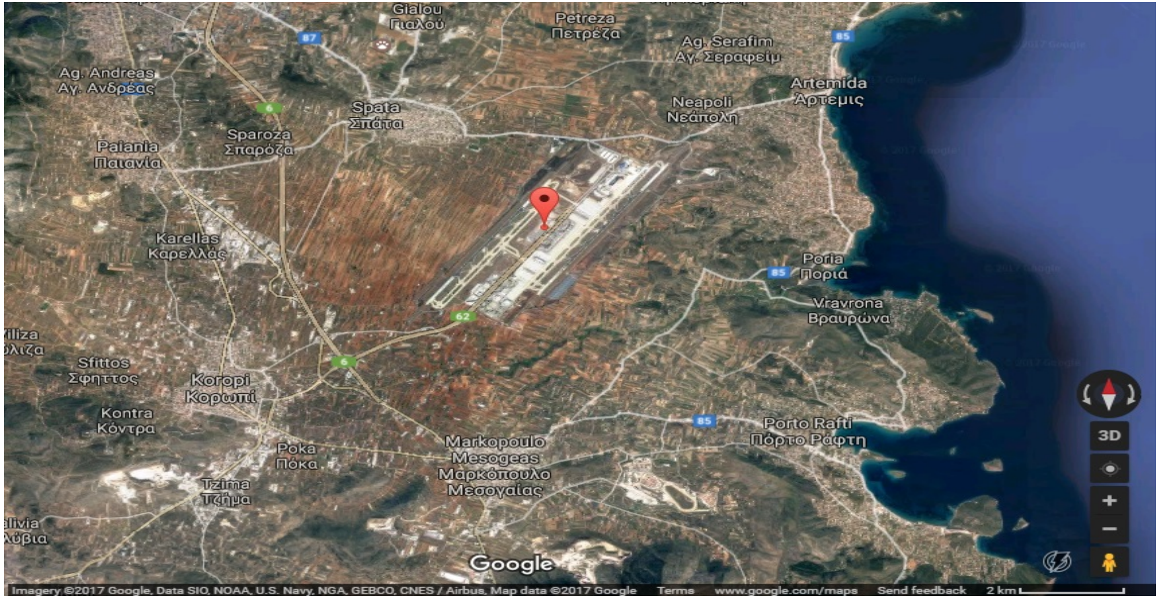


1990

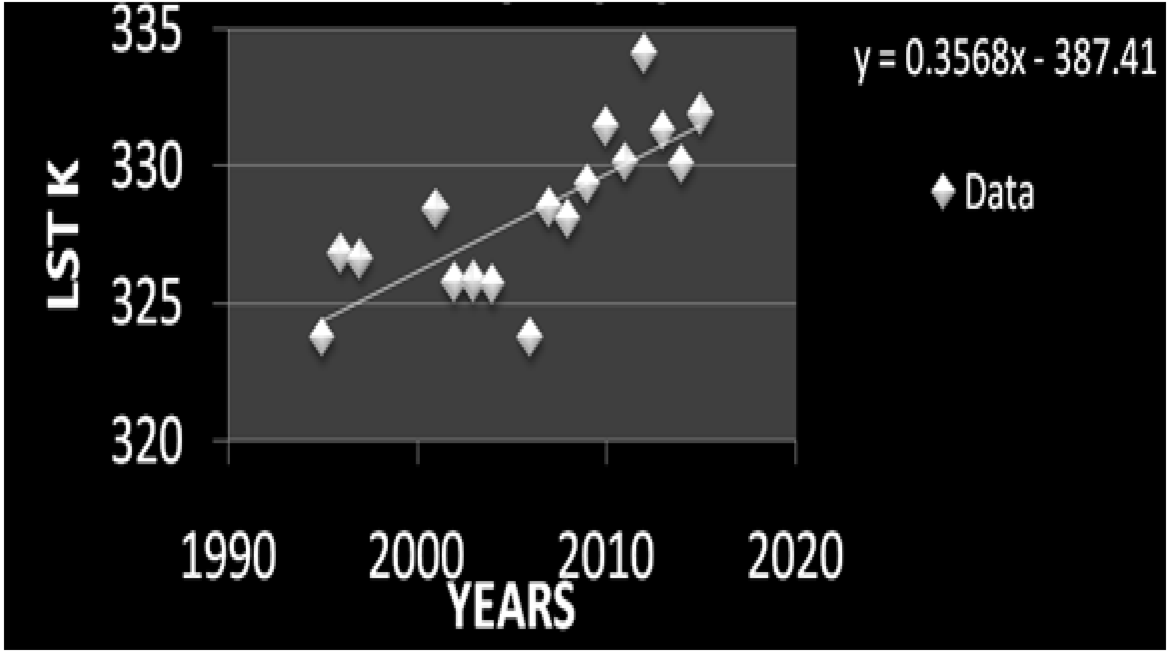


2006

- ❑ Airport since 2001. Previously agricultural/rural areas

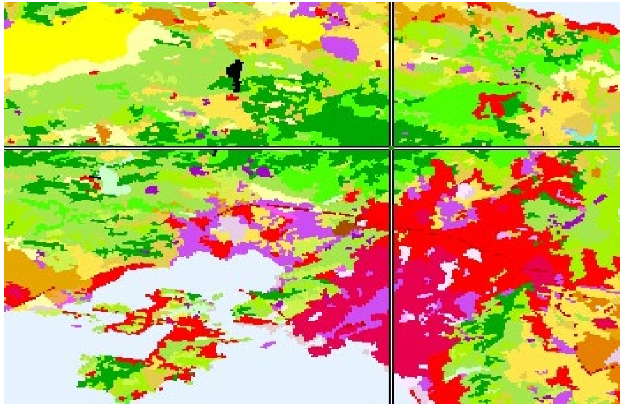


Landscape change – from natural to built



Mean value	**328.320 K**
Trend	**2.1 %**
Increase	**6.8 K**

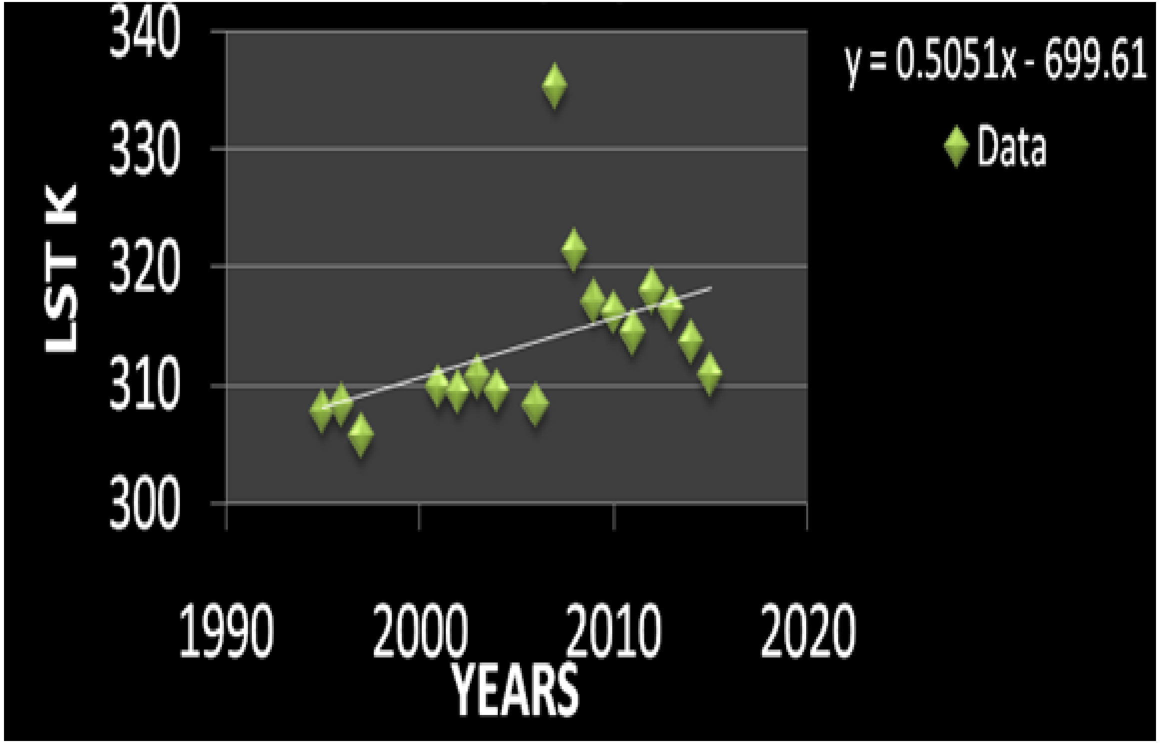
Mountainous area



2006

- ❑ Forested from 1990 to 2007
- ❑ Devastating fire – July 2007
- ❑ Reforestation > 2007

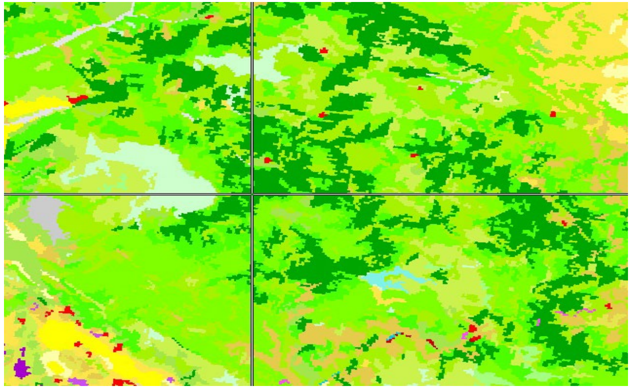
Mountainous area



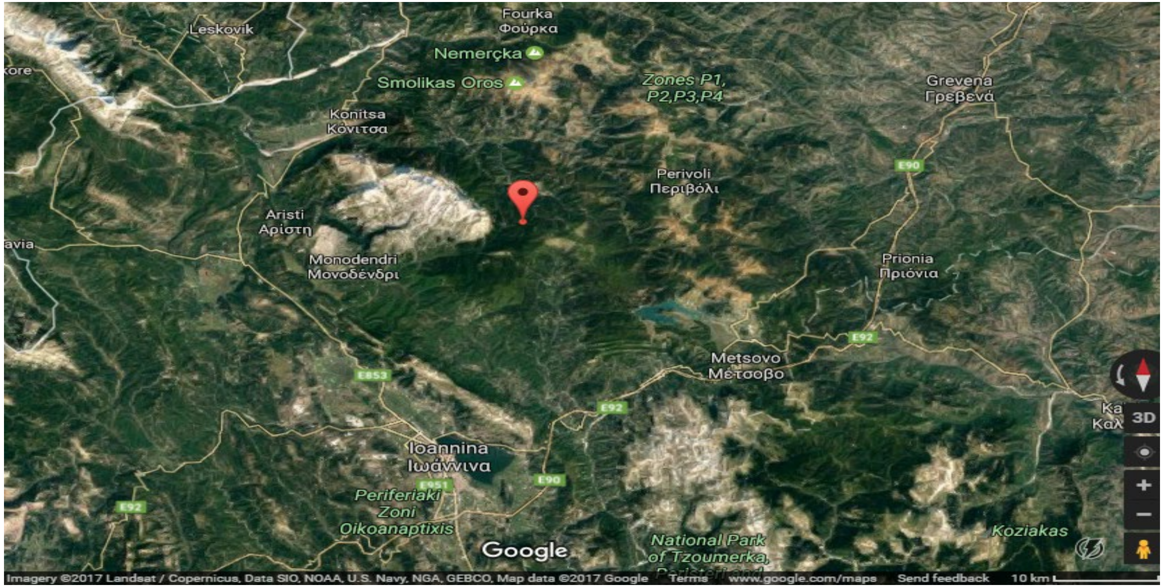
Mean value	313.694 K
Trend	3.2 %
Increase	10 K

Nature reserve (Natura 2000 network)

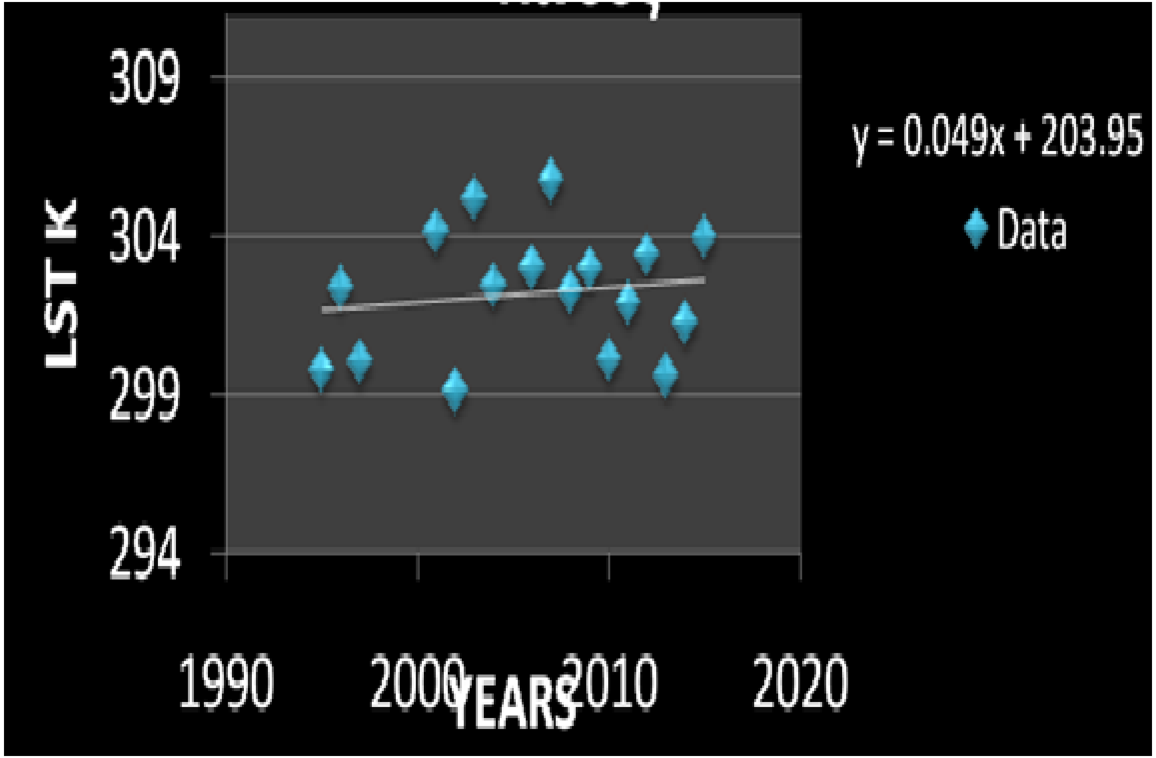
2006



- ❑ Forested area throughout the study period



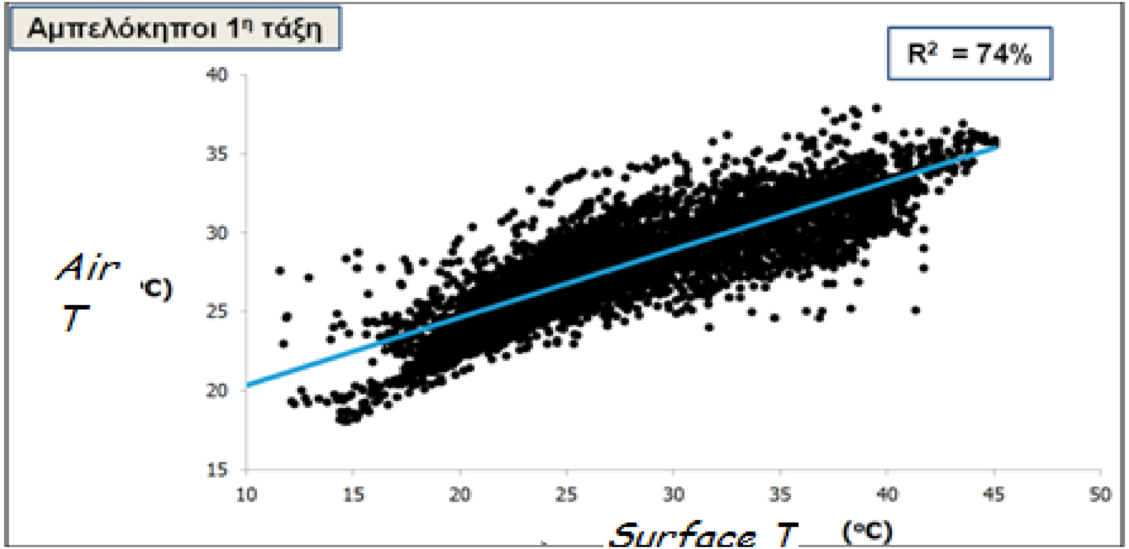
Nature reserve (Natura 2000 network)



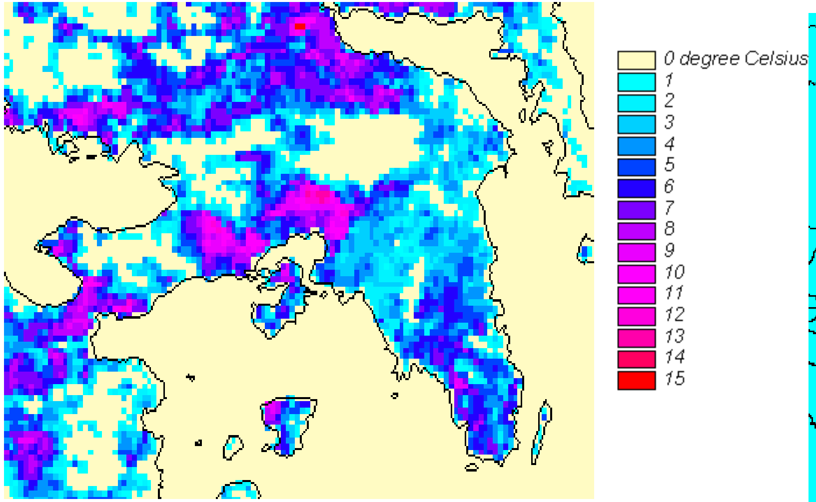
Mean value	302.224 K
Trend	0.3 %
Increase	0.9 K

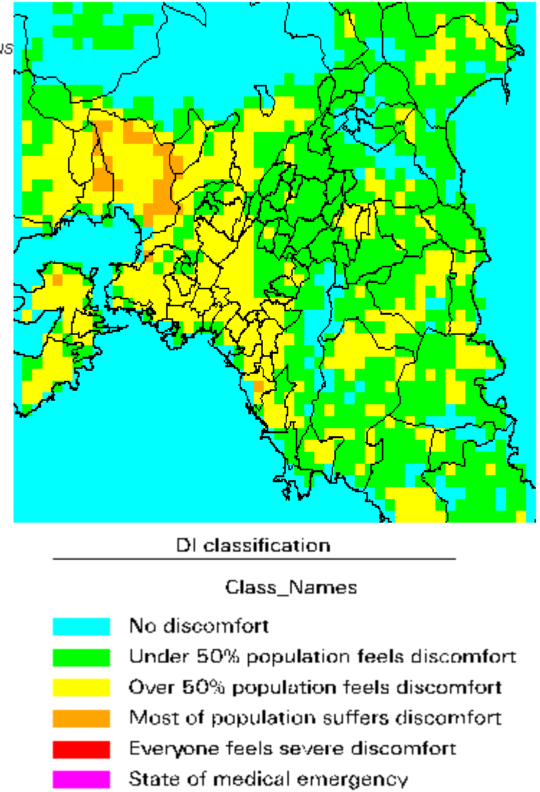
Link LST to air temperature

Important to simulate energy fluxes. But be careful: local applicability



Source: Agathangelidis and Cartalis, 2016

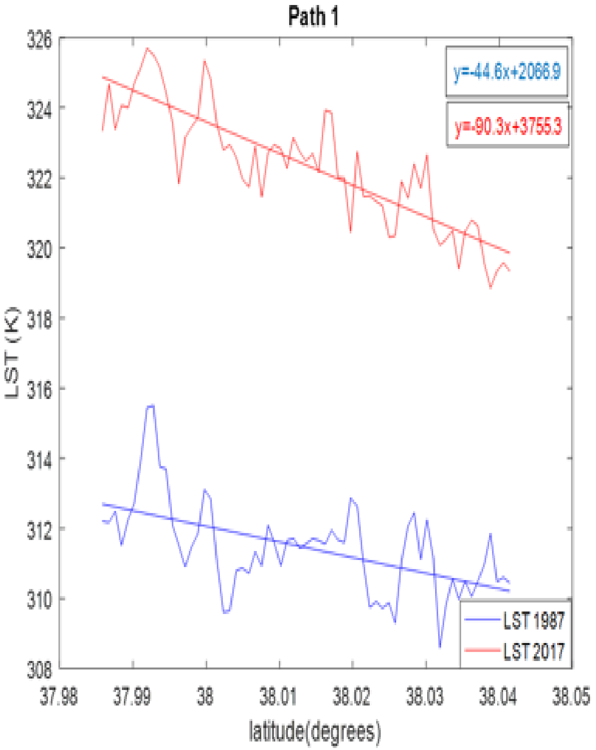




Cooling degree days (left) and Thermal discomfort Index (right)

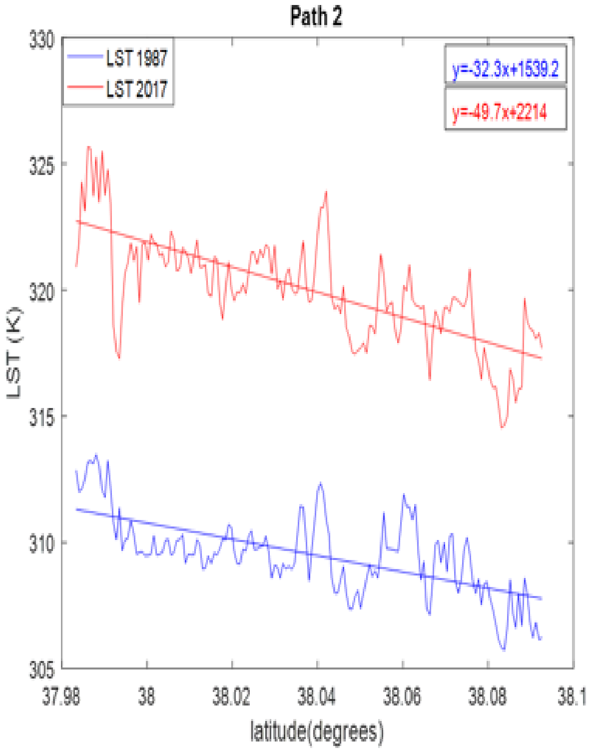
Satellite Remote Sensing and the urban thermal environment

Thermal trajectories



LST trend
1987: 0.57%
2017:1.25%

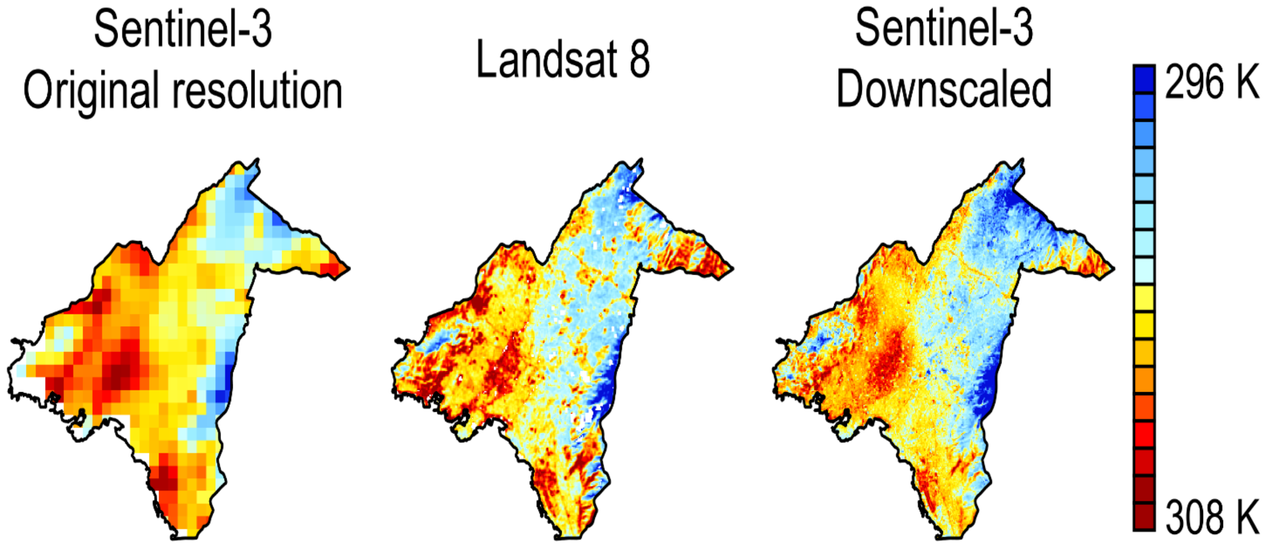
R
1987: -0.54
2017: -0.85



LST trend
1987: 2.01%
2017:2.05%

R
1987: -0.64
2017: -0.72

Downscaling LST

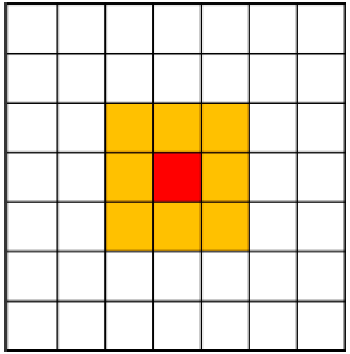


1km, 1-2 per day   30 m, 16 days   100 m, 1-2 per day

Thermal hot spot detection

Critical p-values and z-scores for different confidence levels.

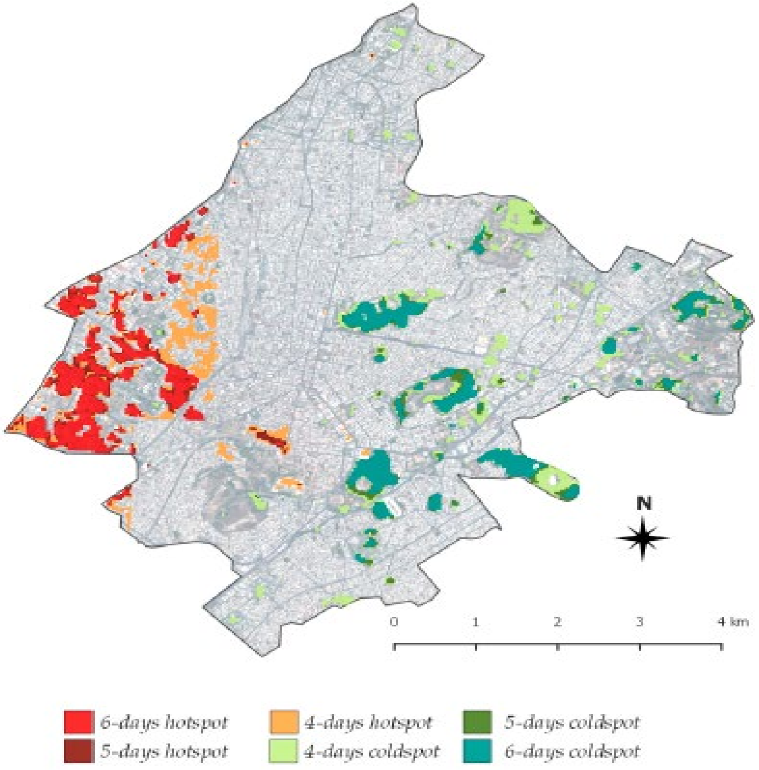
Significance Level (p Value)	Critical Value (z Score)	Confidence Level
−0.01	$z < -3.3$	99.9%
−0.1	$-3.30 < z < -2.58$	99%
0	$-2.58 < z < 2.58$	-
0.1	$2.58 < z < 3.30$	99%
0.01	$z > 3.3$	99.9%



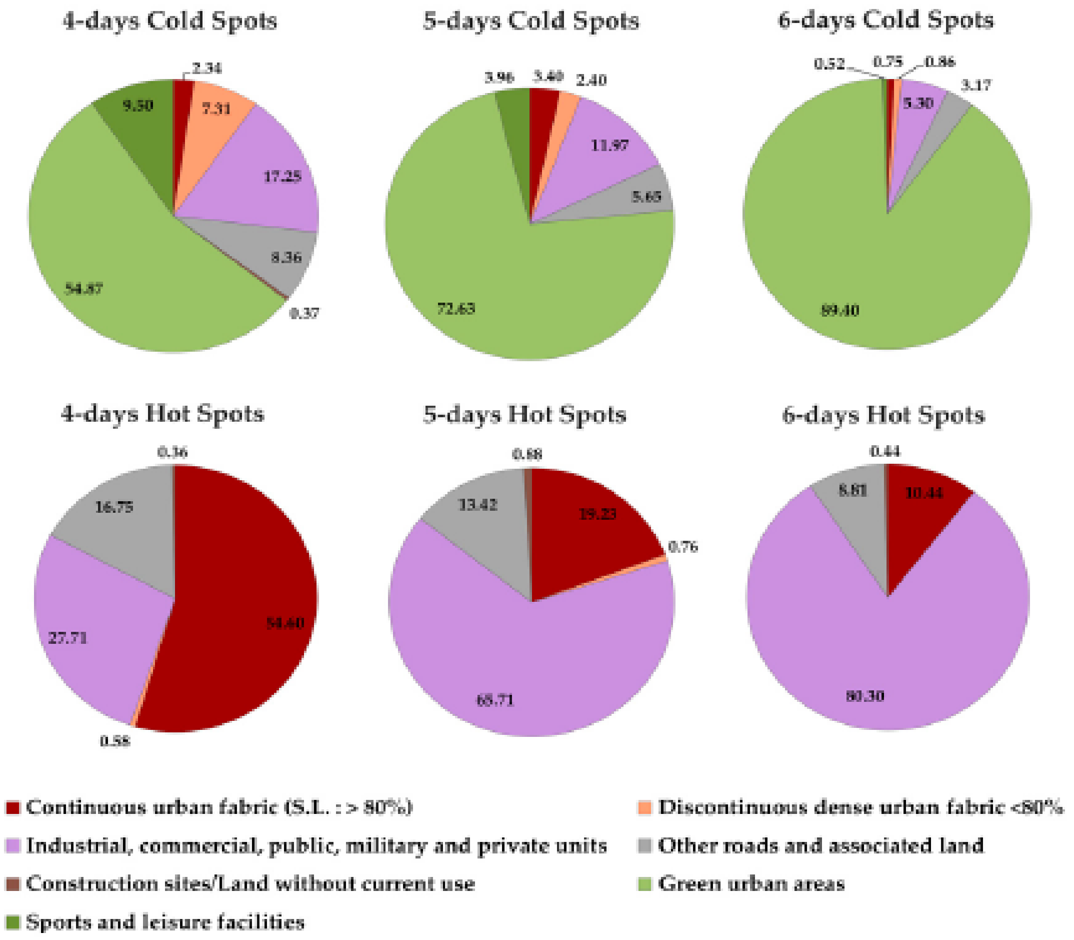
The calculation of the local LST sum for a pixel under consideration (red) includes all of its neighbors (orange).

LST statistics for the "hot spots" and "cold spots" categories (in °K).

	"Hot Spots"			"Cold Spots"		
	Min.	Max.	Mean	Min.	Max.	Mean
6-day	313.94	319.24	317.75	305.57	313.04	308.65
5-day	313.86	318.69	316.19	306.69	312.24	309.78
4-day	313.11	318.37	315.48	306.19	313.56	310.38

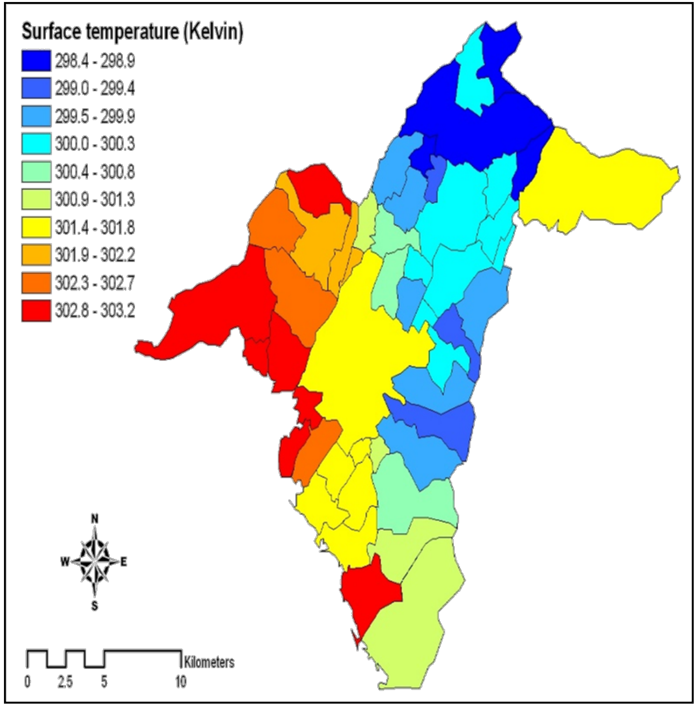


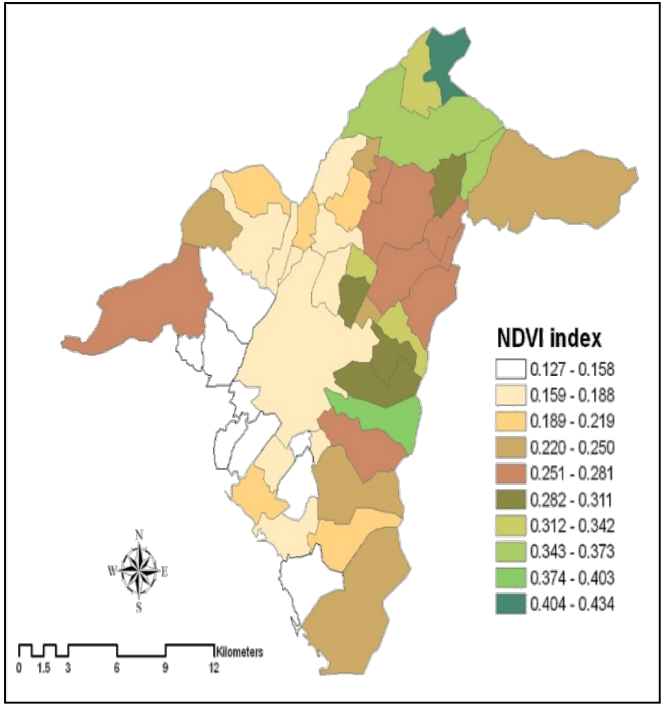
Location of the hot/cold spots within Athens Municipality. (A: old industrial area of Athens, B: the historic center of Athens).



Land use percentages of the "hot spot" and "cold spot" categories.

Greenery in the city





Source: Cartalis et al., 2016

Results – Urban parks

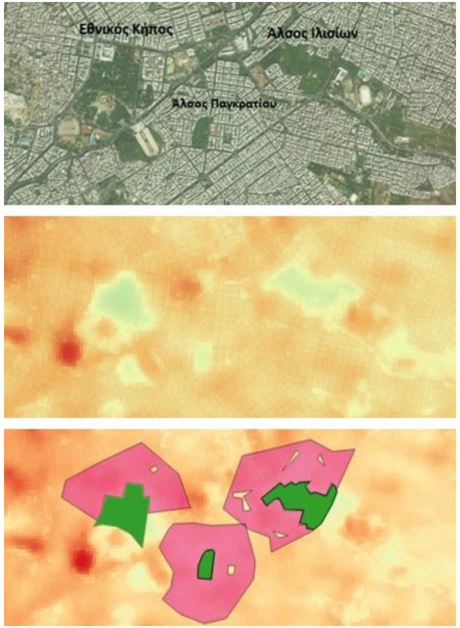
Surface Park Cool Intensity (SPCI) ***<u>(what kind of parks?)</u>***

Surface Park Cool Island (SPCI) is the difference **ΔT = Tu - Tp**

Tu the average Land Surface Temperature of the urban fabric around the park at a radius of 500 meters (excluding other parks or areas with water),

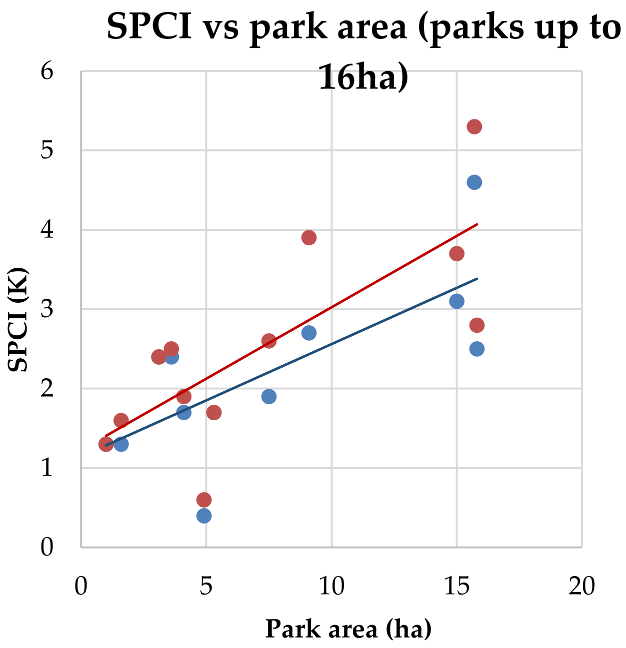
Tp is the average Land Surface Temperature (LST) in the park

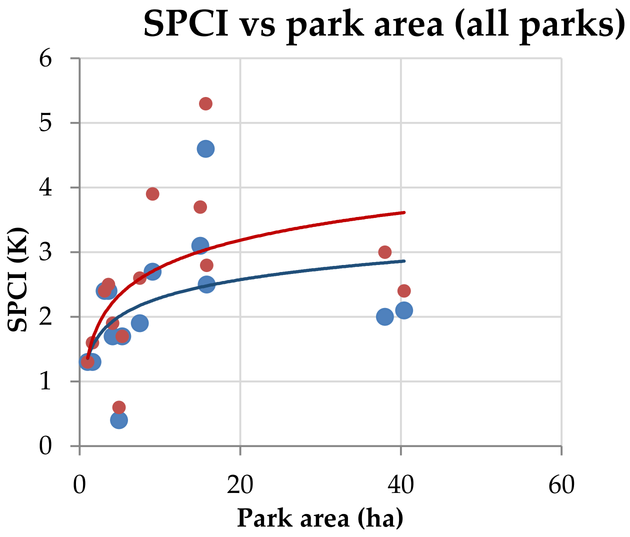
The 500 meters zones are depicted in purple colour.



Results – Urban parks

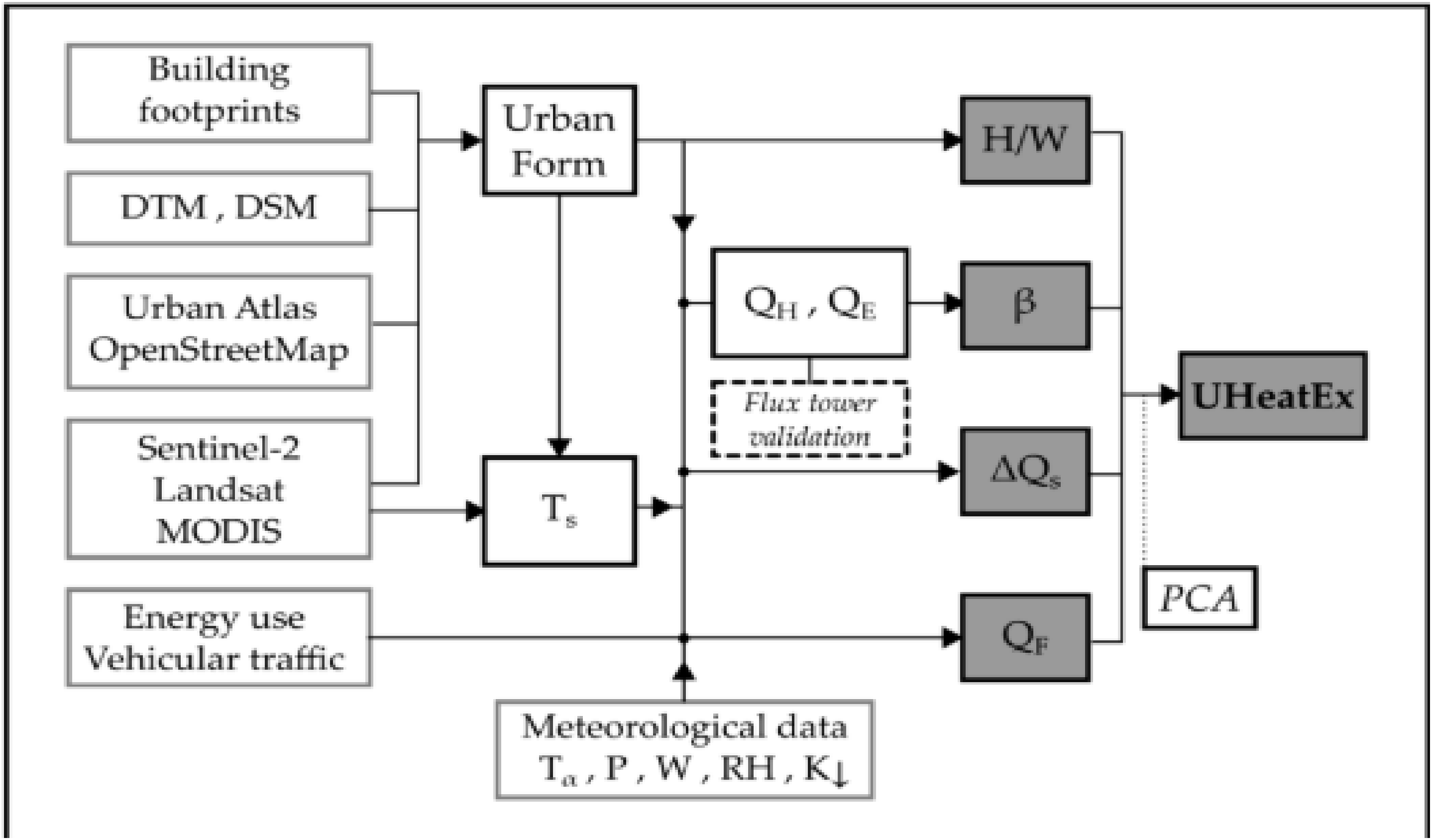
Impact of park area to SPCI: SPCI increases with increasing park size up to sizes around 20 ha and then becomes asymptotic which implies that no matter how bigger the size of the park becomes, SPCI remains almost constant. ***Important to develop many small parks – urban acupuncture***





Working with indicators

Flowchart of the methodology for the estimation of the Urban Heat Exposure (UHeatEx) indicator.



Spatial distribution of the UHeatEx indicator for Athens at 100-meter resolution; scale varying from low (0) to high (10) thermal environmental quality.