

Δορυφορική τηλεπισκόπηση στο θερμικό
υπέρυθρο

Learning Objectives

Τι αφορά η δορυφορική τηλεπισκόπηση στο θερμικό υπέρυθρο?

Ποιοι νόμοι την περιγράφουν;

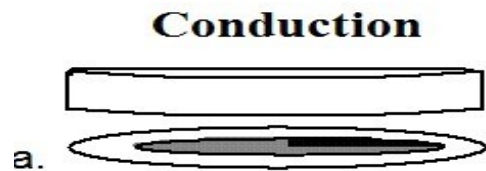
Ποιά η διαφορά μεταξύ της θερμοκρασίας λόγω της κινητικής ενέργειας (kinetic temperature) και της θερμοκρασίας ακτινοβολίας (radiant temperature);

Πως συνδέεται ο συντελεστής θερμικής εκπομπής με τη δορυφορική τηλεπισκόπηση στο θερμικό υπέρυθρο;

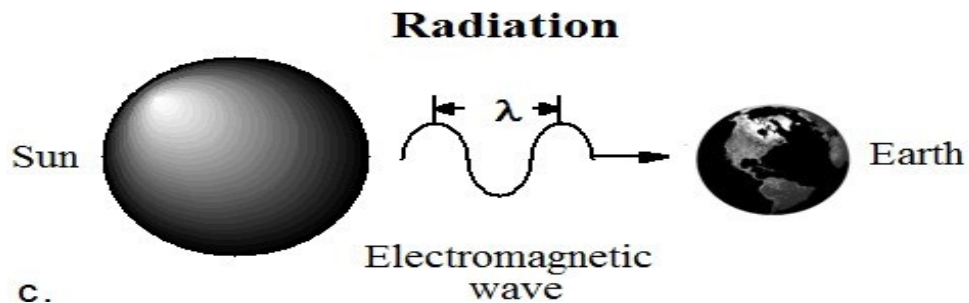
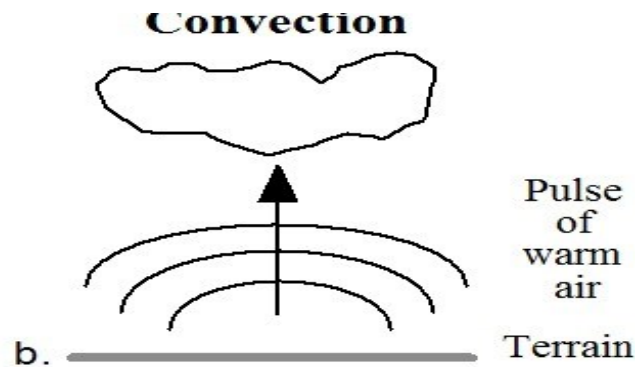
Ποιά τα αναγκαία βήματα για την επεξεργασία μίας δορυφορικής εικόνας στο θερμικό υπέρυθρο;

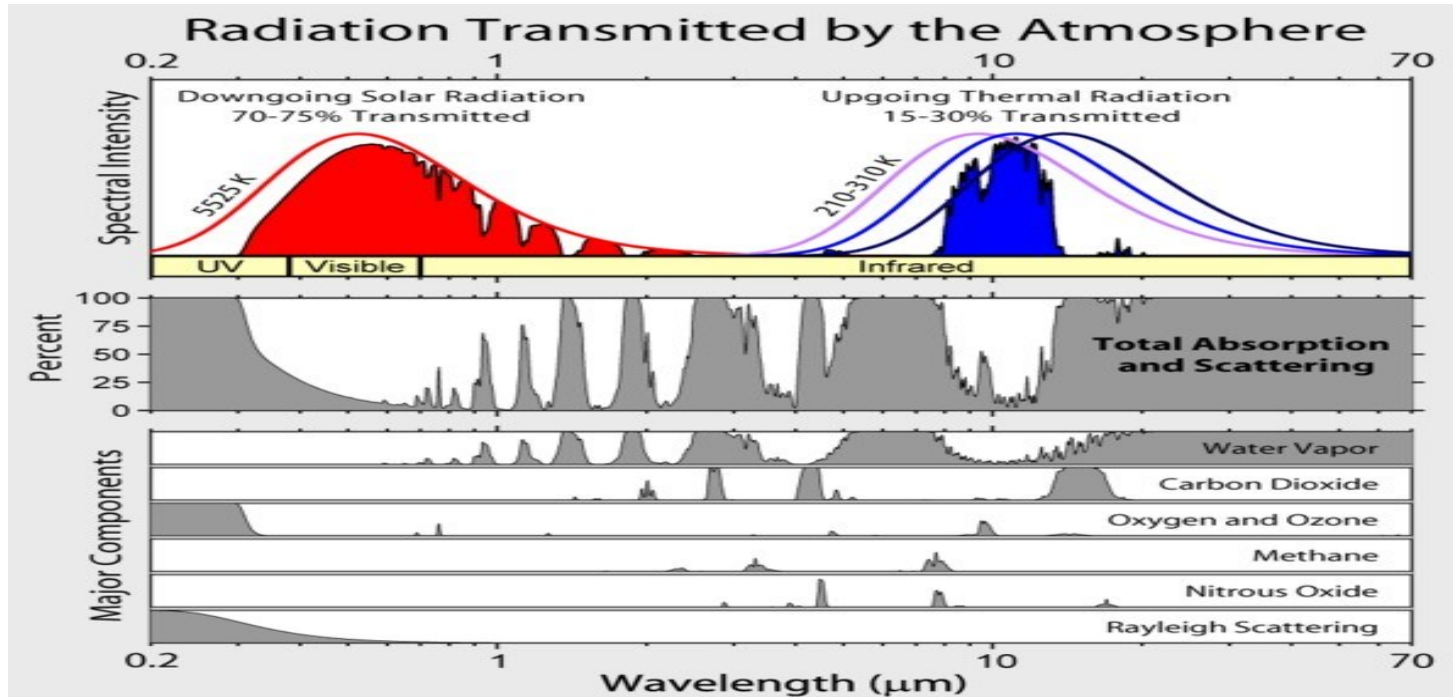
Πως υπολογίζεται η επιφανειακή θερμοκρασία εδάφους και ποια η φυσική της σημασία;

Ποιες εφαρμογές υποστηρίζονται;



Pan
in contact
with burner





Spectral signature = $f(\lambda)$

Εισαγωγικά σημεία

1. Η εσωτερική ενέργεια (λόγω κινητικής ενέργειας) (**internal kinetic heat**) ενός αντικειμένου μετατρέπεται σε ενέργεια ακτινοβολίας (**radiant energy** ή external ή apparent energy).

2. Η ποσότητα ροής ακτινοβολίας που εκπέμπεται από ένα σώμα, συνδέεται με την θερμοκρασία ακτινοβολίας (T_{rad}).

3. Διαπιστώνεται ισχυρή συσχέτιση μεταξύ της πραγματικής (Kinetic) θερμοκρασίας του σώματος και της θερμοκρασίας ακτινοβολίας.

Αυτή είναι η βάση για τη δορυφορική τηλεπισκόπηση στο θερμικό υπέρυθρο.

Όμως η σχέση που διαμορφώνεται δεν είναι ακριβής, με τη θερμοκρασία ακτινοβολίας να είναι λίγο μικρότερη από την πραγματική θερμοκρασία του σώματος (true kinetic temperature).

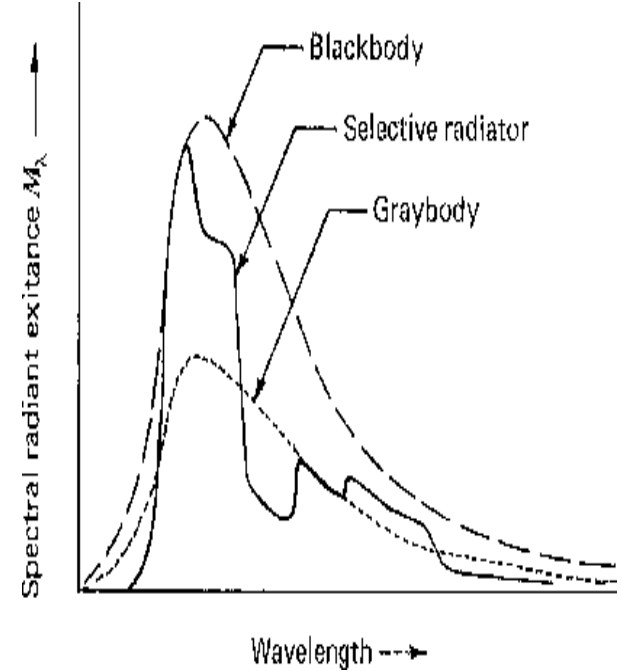
Η διαφορά αυτή οφείλεται στην ιδιότητα της εκπομπής (**emissivity**

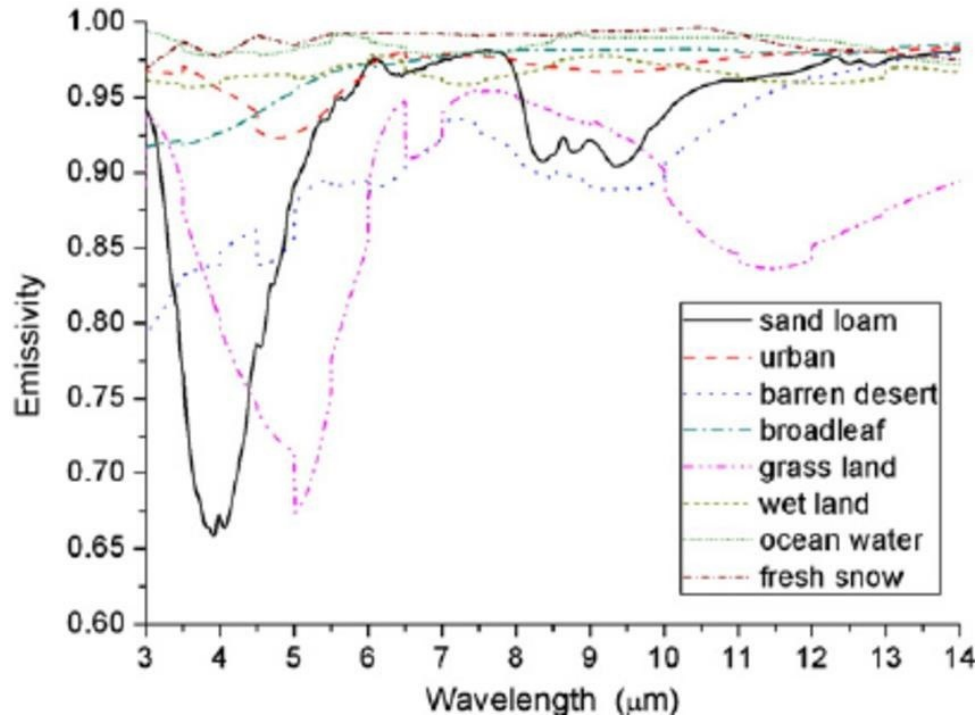
Radiation of real Materials

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

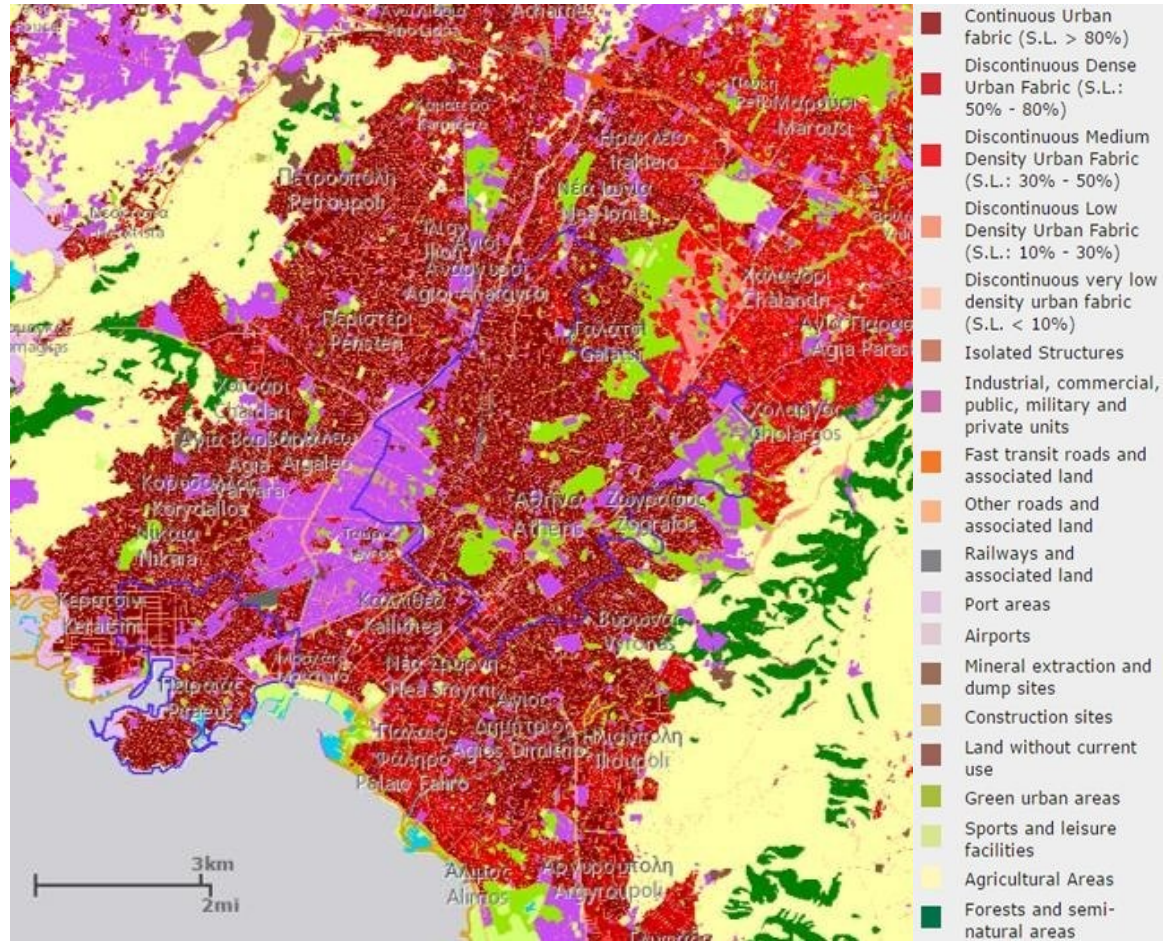
Basic classes:

1. Continuous urban fabric: Housing.
Mean impervious value > 80%.

2. Non continuous urban fabric:
Housing over 20%, open space,
private gardens, disperse vegetation.
Mean impervious value: 10- 80%.

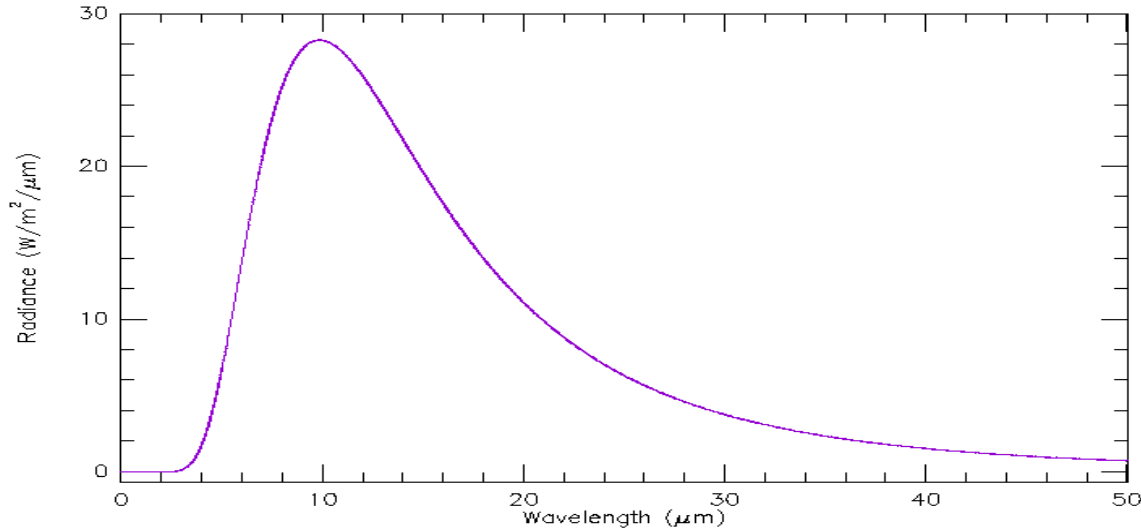
**3. Industrial-Commerical-Public
Buildings:** artificial surfaces (cement,
asphalt, etc.).

4. Urban green: mostly parks



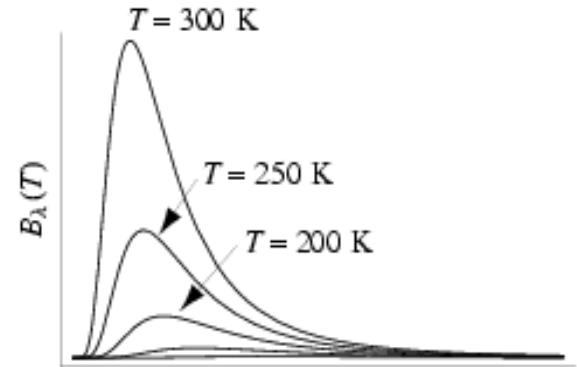
Planck blackbody equation:

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.

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



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

Planck equation for blackbody radiance

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

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

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

Stefan-Bolzman Law for natural object:

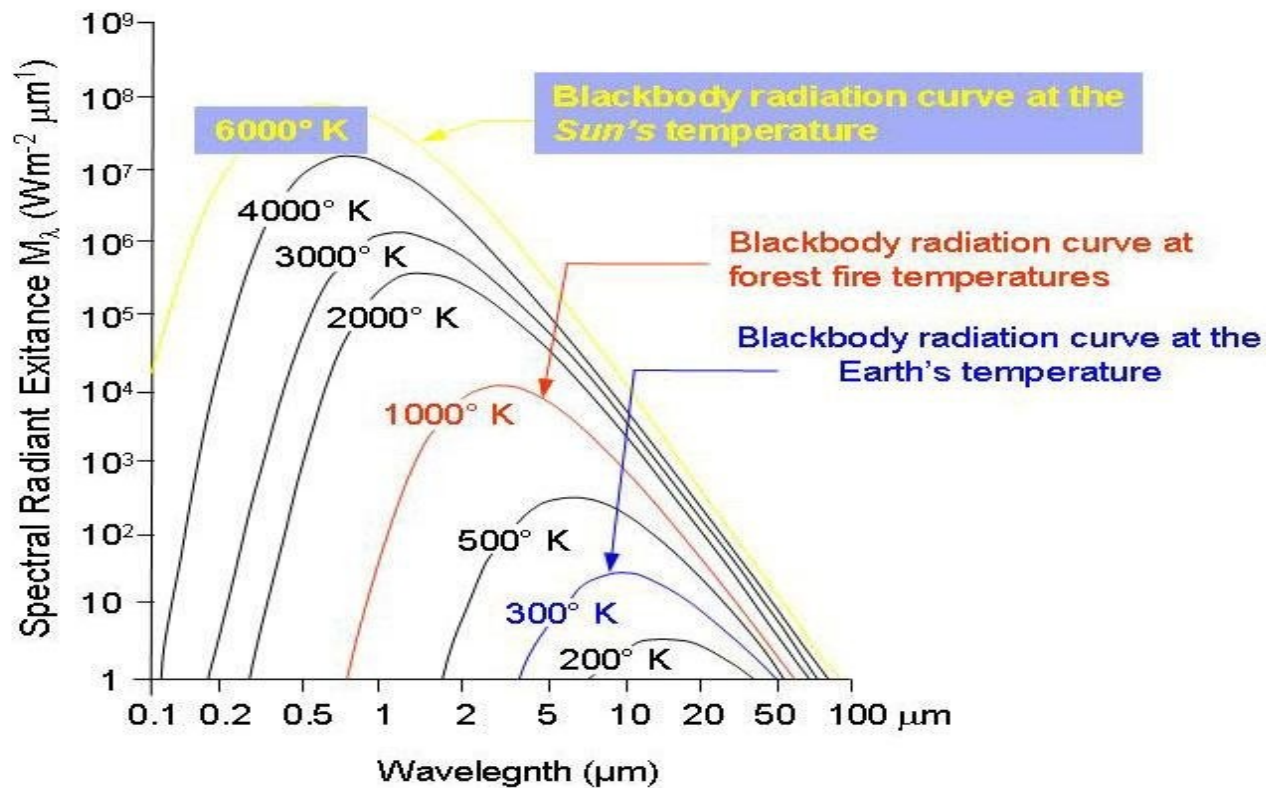
$$B = \epsilon \sigma T_K^4 = \sigma T_R^4$$

$$T_R = \epsilon^{1/4} T_K$$

$$T_K = \frac{T_R}{\epsilon^{1/4}}$$

$$T_R < T_K \text{ by } \epsilon^{1/4}$$

T_K the kinetic temperature



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

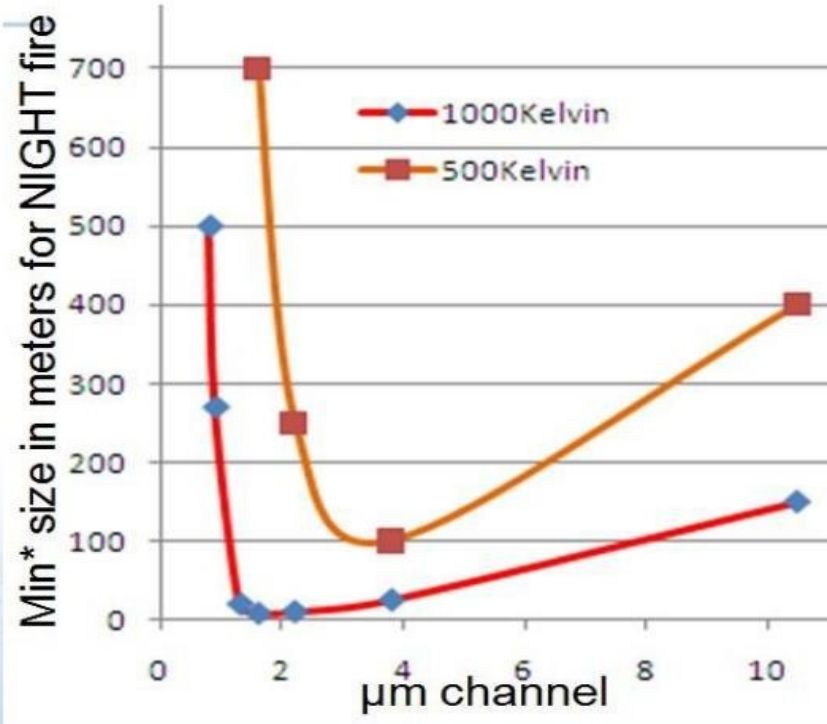
•**first** by 3.9 μm (at ~100m)

•**second** by 2.2 μm (250m)

•**third** by 10.8 μm (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 3.9 μm



Wavelength in Micrometers, μm

Η έννοια του κυρίαρχου μήκους κύματος (**dominant wavelength**)

Παρέχει πληροφορίες αναφορικά με το τμήμα εκείνο του θερμικού υπέρυθρου το οποίο χρειάζεται να αξιοποιήσουμε.

Για παράδειγμα, αν εξετάζουμε μία δασική πυρκαγιά των **800 °K** με κυρίαρχο μήκος κύματος περίπου **3.62 μm**, τότε η φασματική περιοχή αναφοράς είναι **3-5 μm**.

Αν ενδιαφερόμαστε για στερεό έδαφος με θερμοκρασία περίπου **300 °K** και κυρίαρχο μήκος κύματος **9.66 μm**, τότε ενδείκνυται η περιοχή 8-14 μm.

Kirchhoff's radiation law

Σύμφωνα με το νόμο του Kirchhoff για ένα μέλαν σώμα: $\alpha_\lambda = \varepsilon_\lambda$

$$\text{Αρα } 1 = r_\lambda + \alpha_\lambda + \tau_\lambda$$

$$1 = r_\lambda + \varepsilon_\lambda + \tau_\lambda$$

Ομως για τα περισσότερα στερεά σώματα $\tau_\lambda = 0$

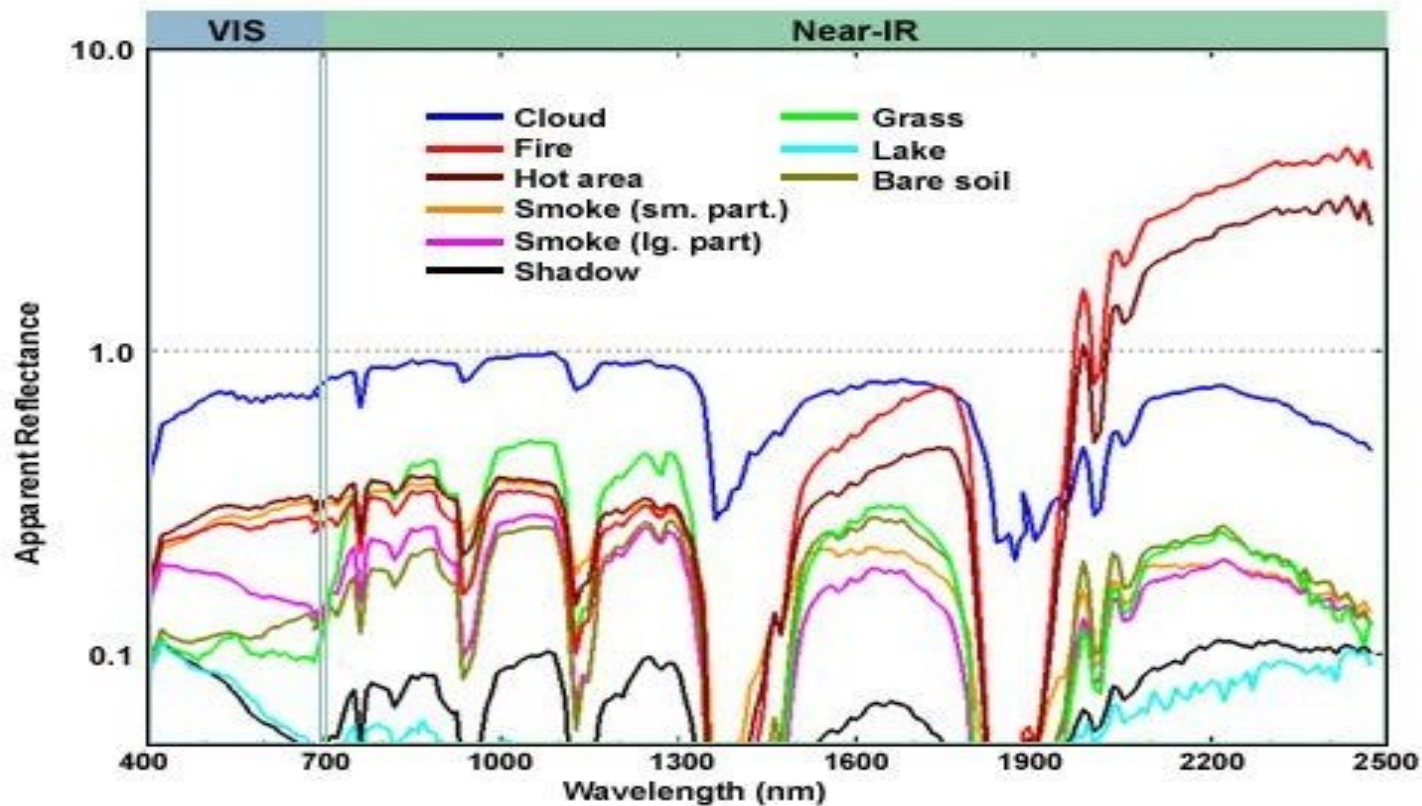
$$\text{Αρα: } 1 = r_\lambda + \varepsilon_\lambda$$

που σημαίνει ότι όσο μεγαλύτερη η τιμή της ανακλαστικότητας ενός αντικειμένου τόσο μικρότερη η τιμή του συντελεστή εκπομπής και αντίστροφα.

Ο συντελεστής εκπομπής ενός σώματος εξαρτάται από τους εξής παράγοντες:

- χρώμα
- τραχύτητα επιφάνειας (τραχεία > λεία)
- περιεχόμενη υγρασία (υγρό έδαφος > ξηρό έδαφος)
- field-of-view/resolution
- μήκος κύματος

Vis & Near IR Spectral Signatures



Σύγκριση φασματικών περιοχών

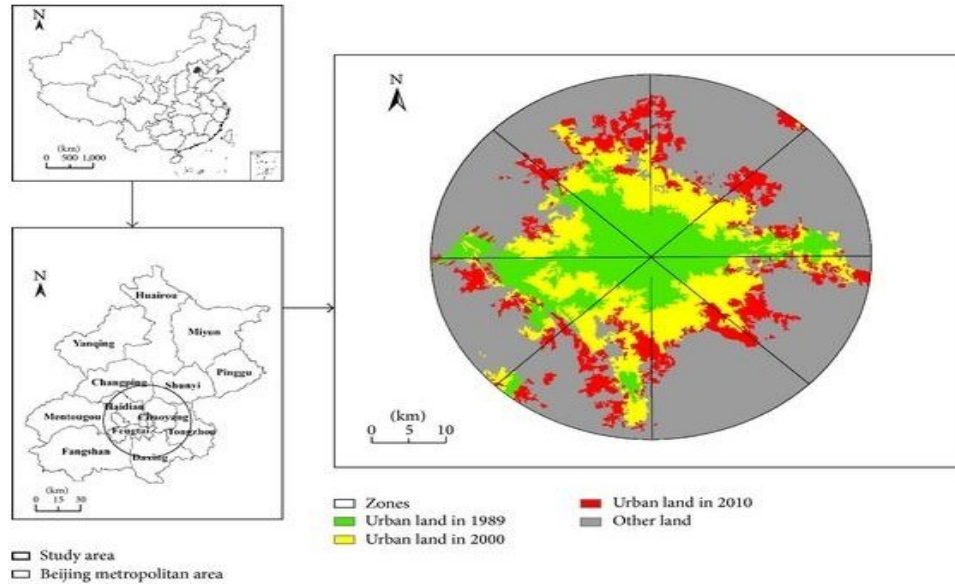
Near infrared (1.6 μm)	<ul style="list-style-type: none">More adequate for smoke detection than 3.9 μmSmall fires not visibleNo CO₂ absorption (higher fire temperature)High sub pixel sensitivity
Middle infrared (3.9 μm)	<ul style="list-style-type: none">High temperature sensitivity - major sub pixel effects (hot spots are easily detected)Negligible absorption by atmospheric humidityClose to a CO₂ absorption band, 4-7 Kelvin signal reductionBrightness is temperature of the CO₂ layer above the fire
Thermal infrared (10.8 μm)	<ul style="list-style-type: none">1-2 Kelvin absorption by atmospheric humidityNo signal reduction by CO₂Lower temperature sensitivity (small subpixel effects)No risk of sensor blinding by firesLow values compared with 3.9 μm due to semi transparent cloud or smoke

Υπολογισμός επιφανειακής
θερμοκρασίας εδάφους
(land surface temperature - LST)

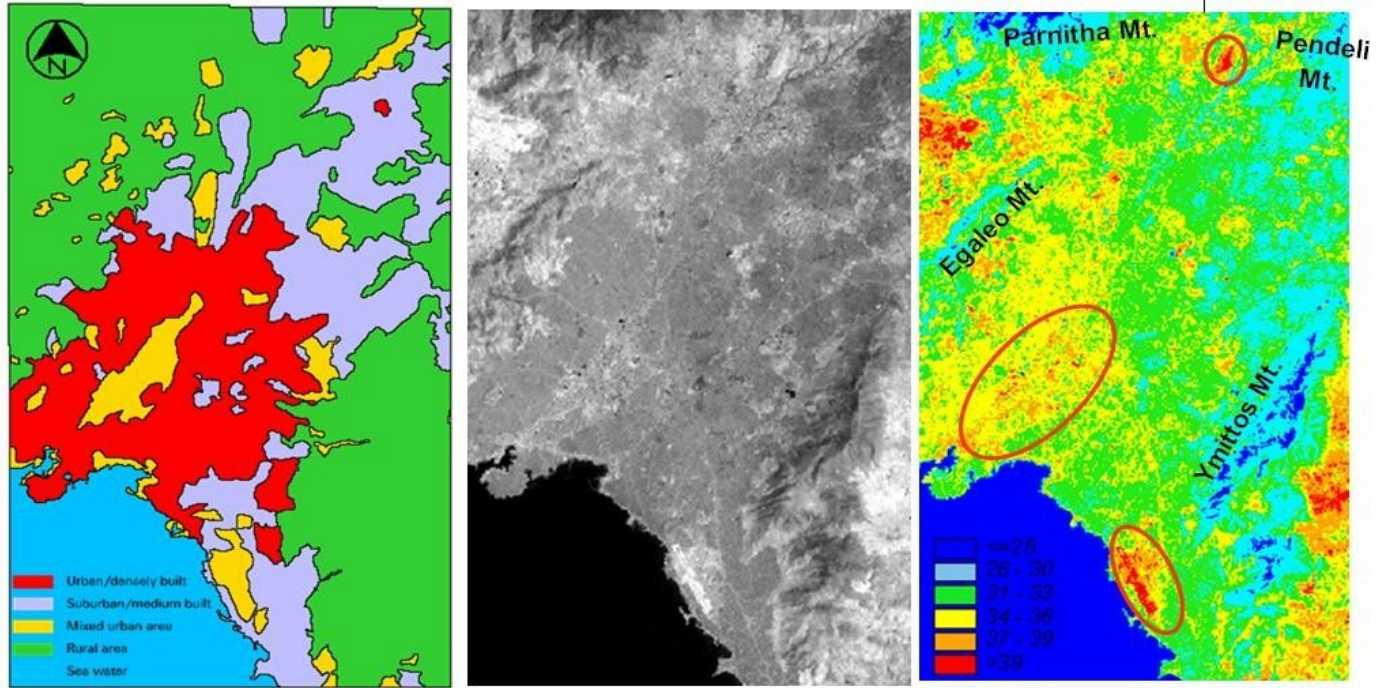
Βήμα 1. Δημιουργία βάσης δεδομένων

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]													

Βήμα 2. Προσδιορισμός LU/LC



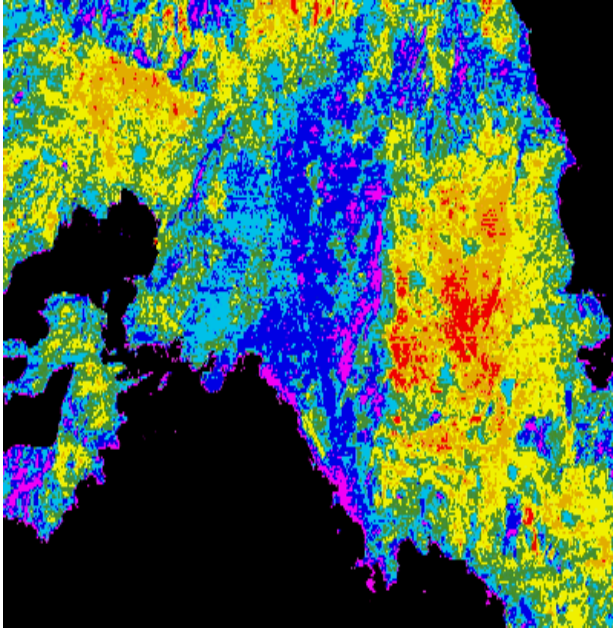
The spatial distribution of urban land in Beijing during 1989–2010.



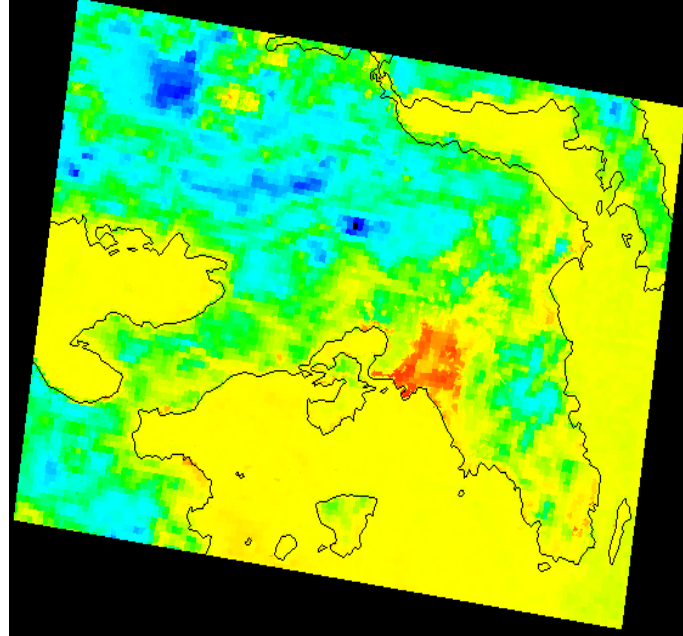
Left to right: Land cover, satellite image in the visible, thermal image

Βήμα 3. Επιλογή των κατάλληλων Δ.Ι. (χώρος – χρόνος)

120m resolution

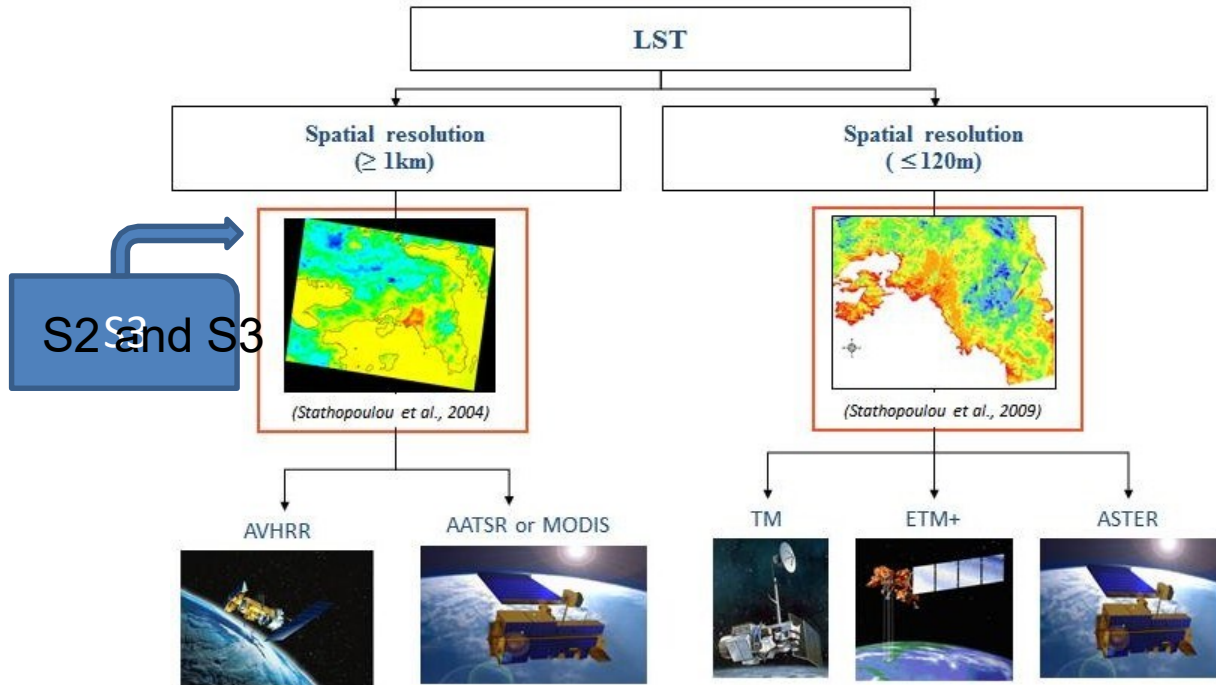


1.1 km resolution

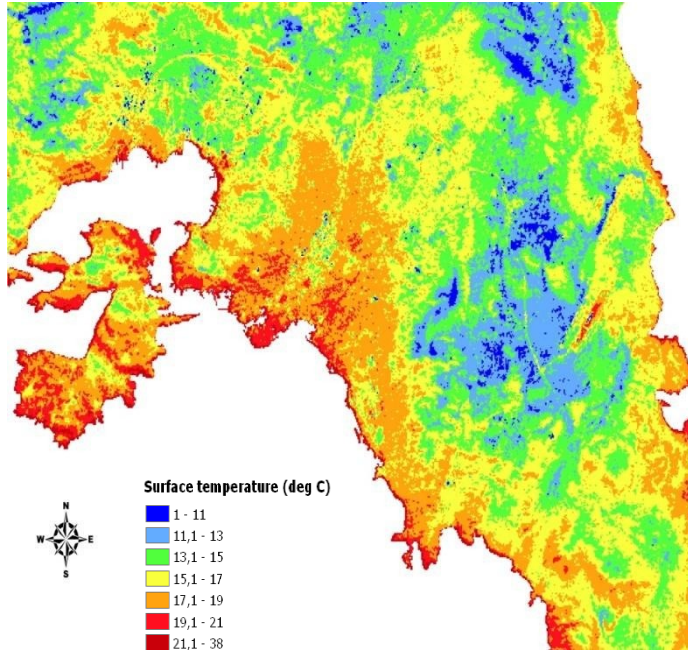


Source: processing by C.Cartalis

Βήμα 4. Επιλογή του κατάλληλου δορυφόρου – Συνδυασμός δεδομένων

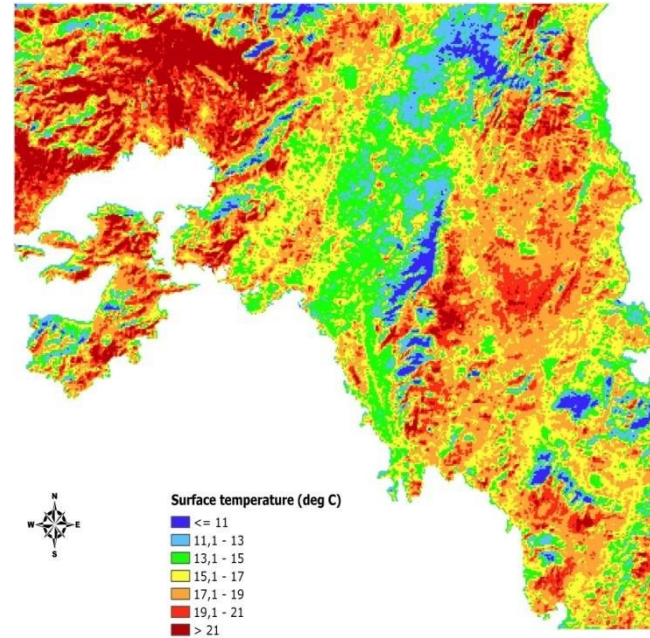


Βήμα 5. Ποια ώρα της ημέρας;



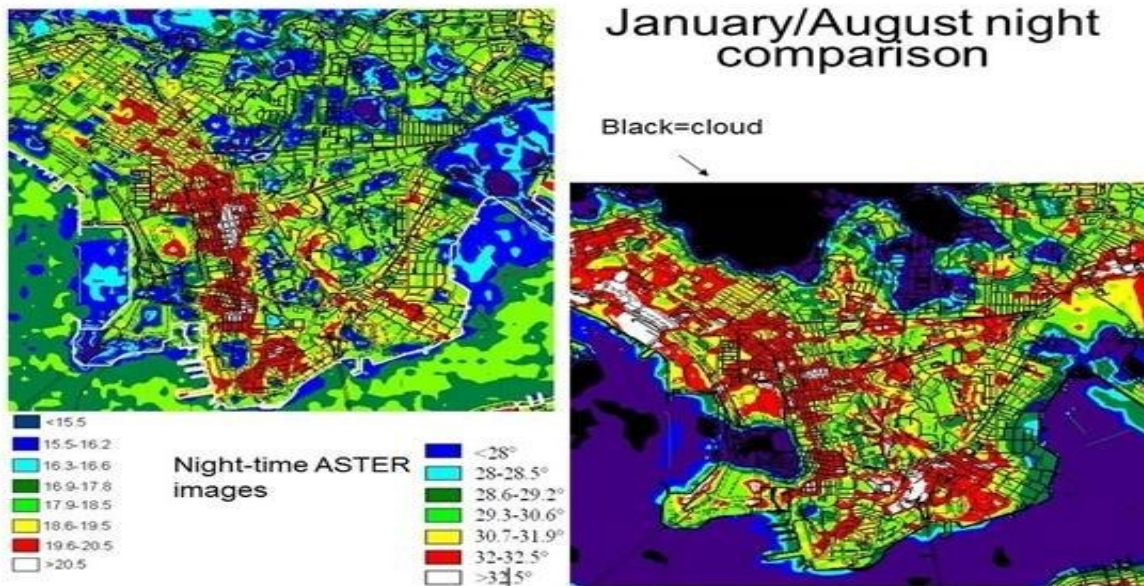
22:32 local time

Source: processing by C. Cartalis



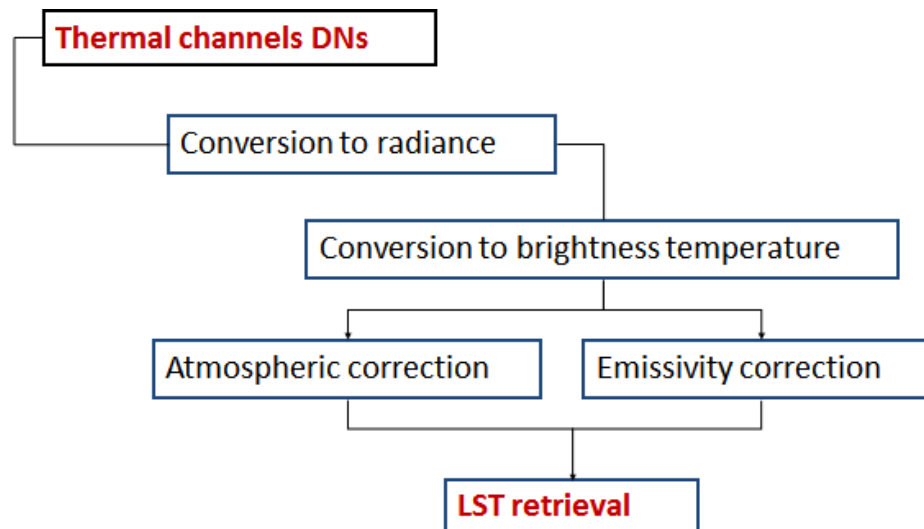
10:30 local time

Βήμα 6. Ποια περίοδο του έτους;

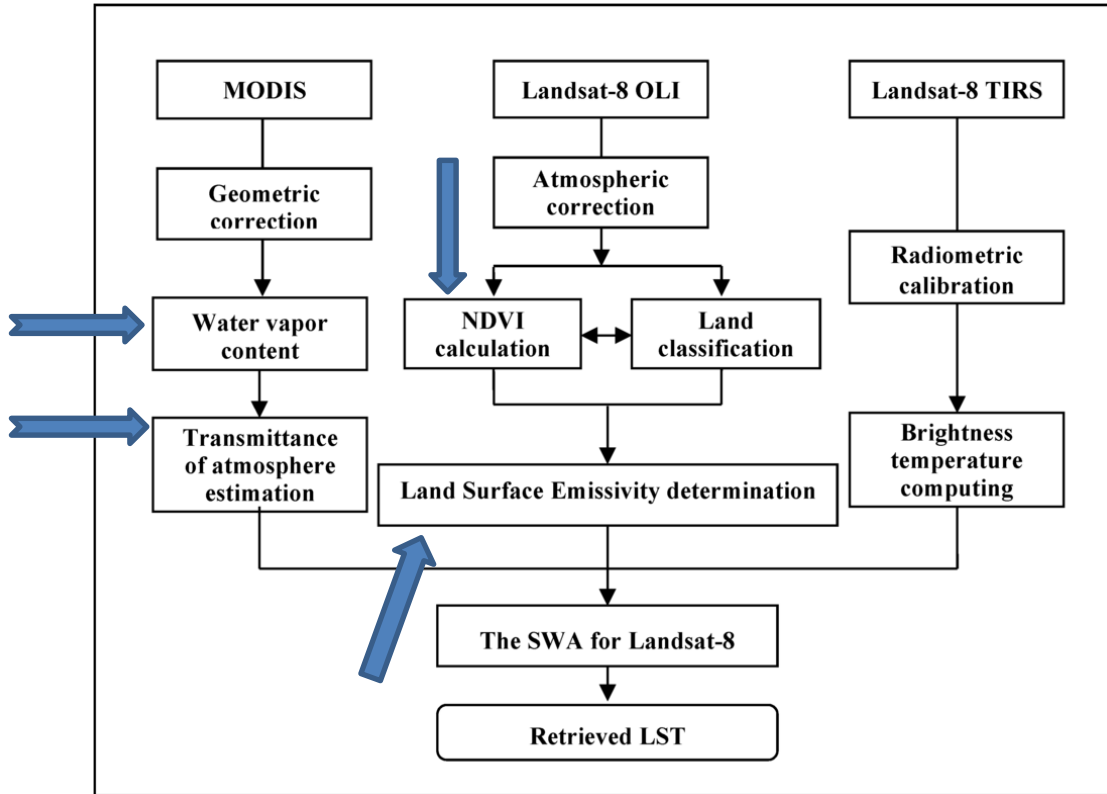


Source: The Hong Kong Polytechnic University

Βήμα 7. Μετατροπή και ανάκτηση (convert and retrieve)



Overall LST accuracy: ± 2 Kelvin



Ανάκτηση LST από Landsat TM

$$L = 0.0056322 \times DN + 0.1238$$

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

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

$$LST = \frac{T_b}{1 + (\lambda \times T_b / \rho) \ln \epsilon}$$

$$\rho = \frac{h \times c}{\sigma}$$

where λ is the wavelength of emitted radiance ($\lambda = 11.5 \mu\text{m}$), σ is the Boltzmann constant ($1.38 \times 10^{-23} \text{ J/K}$), and h is the Planck's constant ($6.626 \times 10^{-34} \text{ Js}$), C is the velocity of light ($2.998 \times 10^8 \text{ m/s}$).

Ανάκτηση LST από Moderate Resolution Imaging Spectroradiometer (MODIS) (Aqua-Terra)

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 (T_s), (Jiménez-Muñoz et al., 2008):

T_s (land surface temperature) = $T_i + c_1 (T_i - T_j) + c_2 (T_i - T_j)^2 + c_0 + (c_3 + c_4 * W) (1 - \epsilon) + (c_5 + c_6 * W) \Delta\epsilon$ where:

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

ϵ : the mean emissivity, $\epsilon = 0.5(\epsilon_i + \epsilon_j)$,

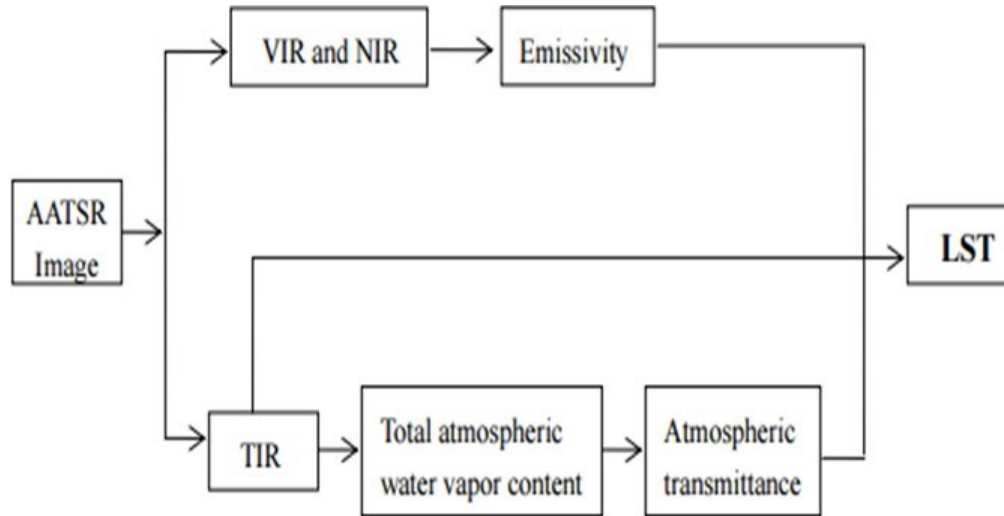
$\Delta\epsilon$: the emissivity difference, $\Delta\epsilon = (\epsilon_i - \epsilon_j)$,

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

$c_0 - c_6$: 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.

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):

$$T_{\text{Sentinel3},30} = T_{\text{Sentinel3},1000} * T_{\text{landsat},30}^{27/7/16} / T_{\text{landsat},30 \rightarrow 1000}^{27/7/16}$$

$$T_{\text{Sentinel3},30} = T_{\text{Sentinel3},1000} * \epsilon_{\text{landsat},30} / \epsilon_{\text{landsat},30 \rightarrow 1000}$$

$T_{\text{Sentinel3},30}$

Corrected image high spatial resolution

$T_{\text{Sentinel3},1000}$

Initial image of low spatial resolution

$T_{\text{landsat},30}^{27/7/16}$

Initial value of high spatial resolution (LANDSAT)

$T_{\text{landsat},30 \rightarrow 1000}^{27/7/16}$

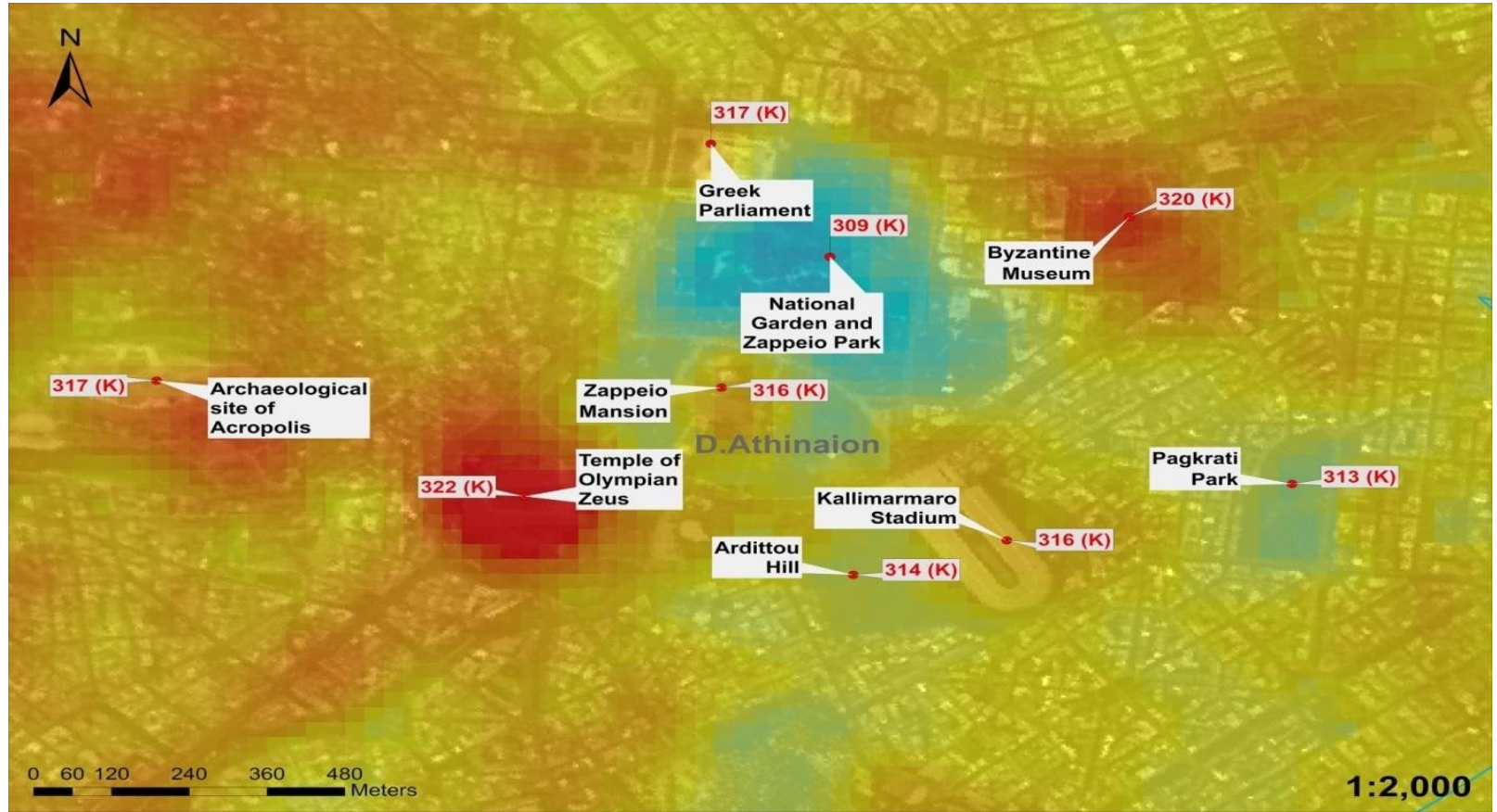
Mean LST for an area corresponding to the area of Sentinel – 3 (LANDSAT)

$\epsilon_{\text{landsat},30}$

Emissivity for an image of high spatial resolution (LANDSAT)

$\epsilon_{\text{landsat},30 \rightarrow 1000}$

Mean emissivity for an area corresponding to the area of Sentinel 3

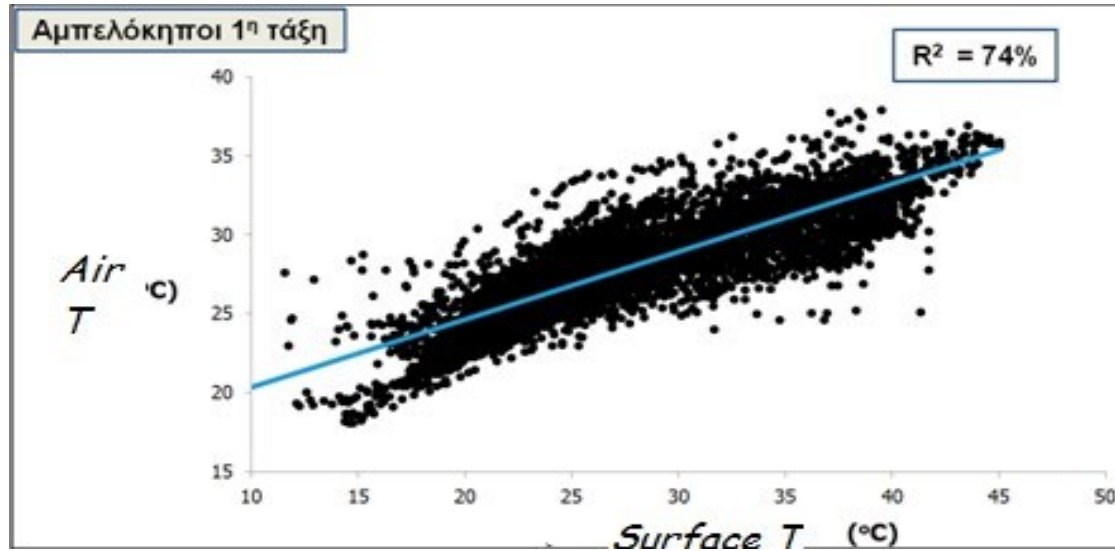


Courtesy. National Observatory of Athens

ΕΦΑΡΜΟΓΕΣ

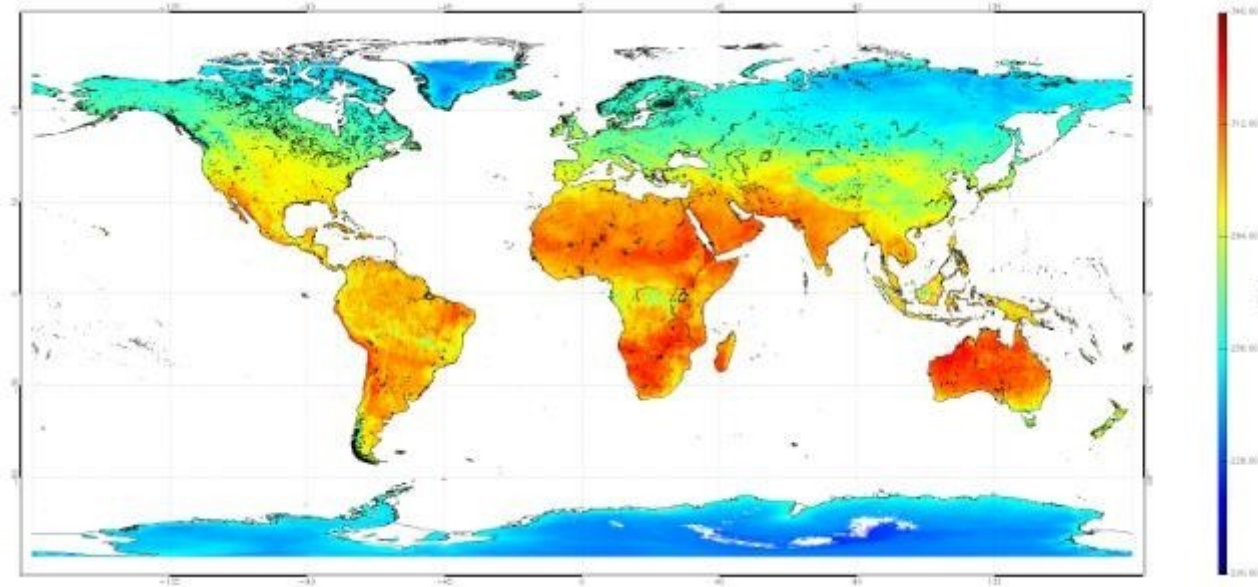
Link LST to air temperature

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



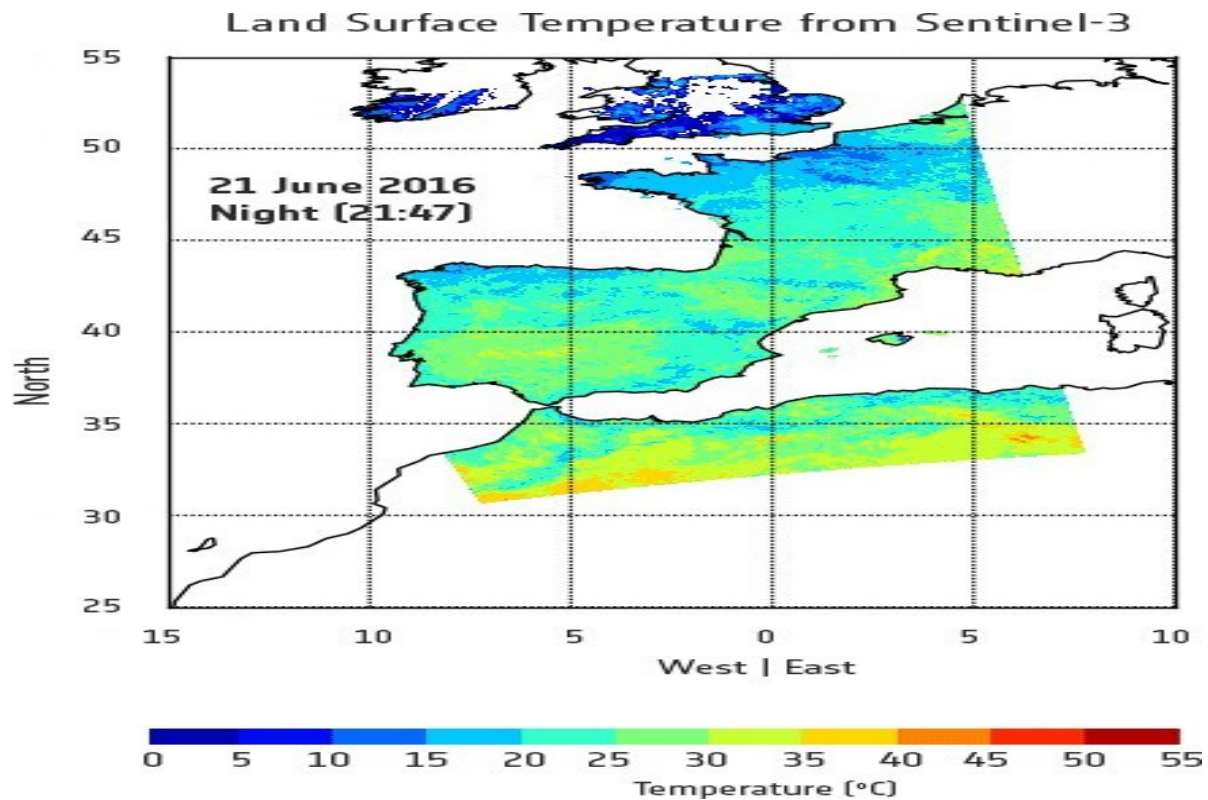
Source: Agathangelidis and Cartalis, 2016

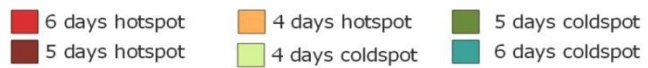
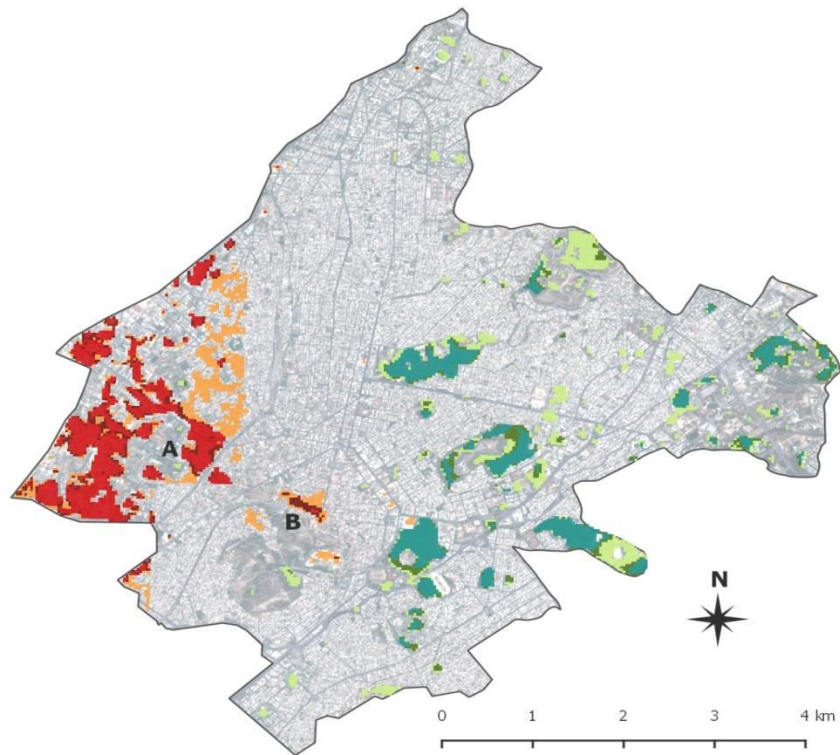
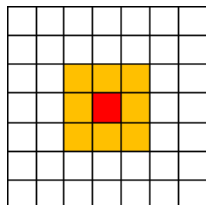
Climate Dynamics



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.

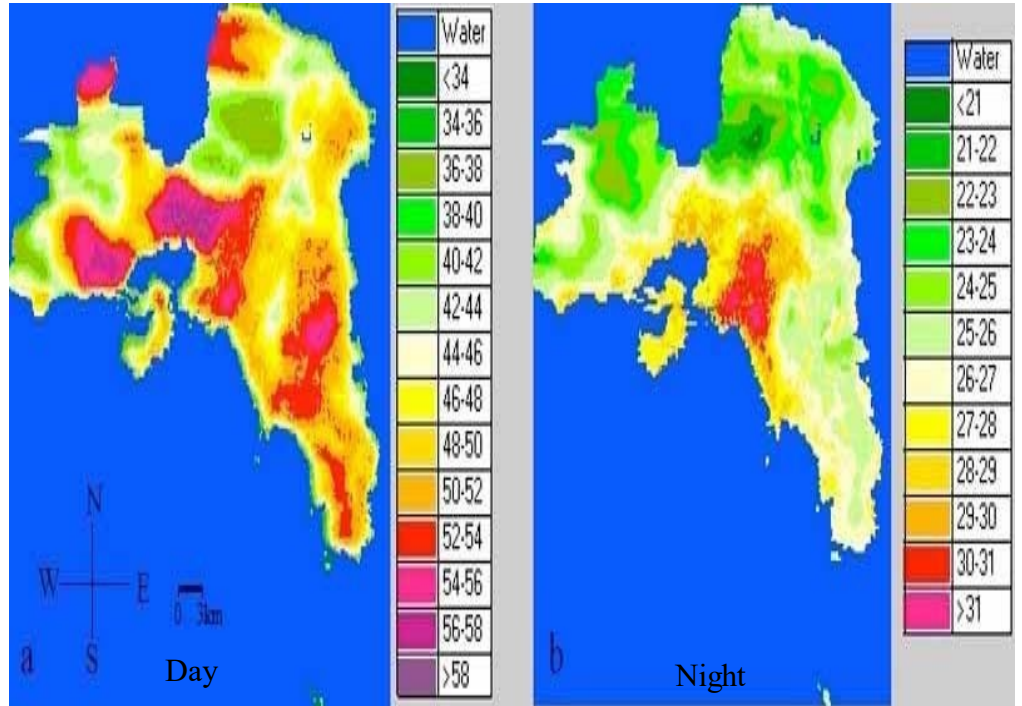
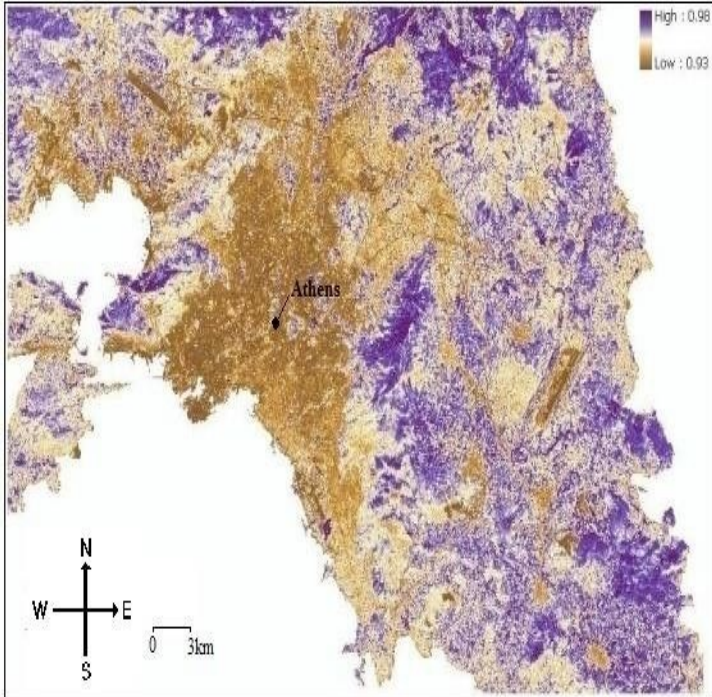
Land surface
temperature
dynamics



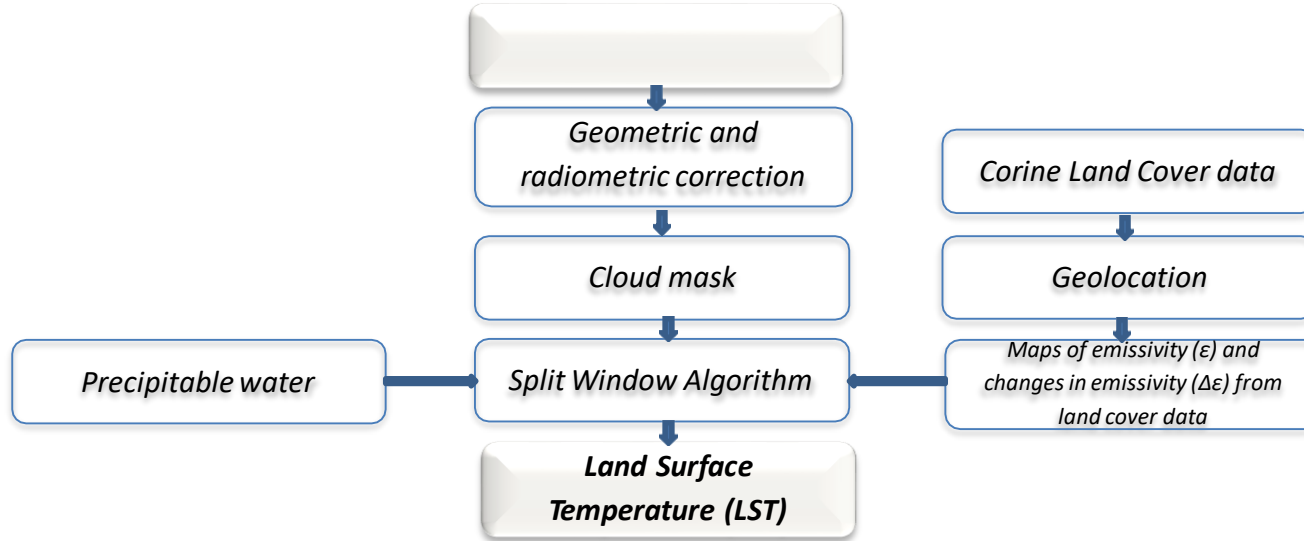


**ΤΑΣΕΙΣ ΣΤΗΝ ΕΠΙΦΑΝΕΙΑΚΗ ΘΕΡΜΟΚΡΑΣΙΑ
ΕΔΑΦΟΥΣ**

Support of Urban Resilience and Climate Adaptability Plans (Land surface emissivity (left) and Land Surface Temperature (right))

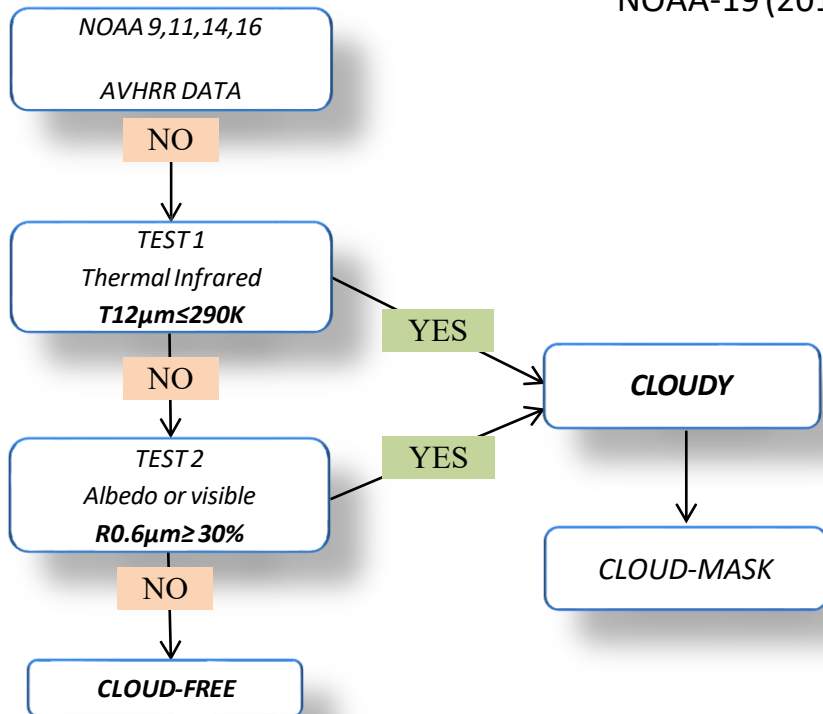


Long term trends in LST for land surface dynamics

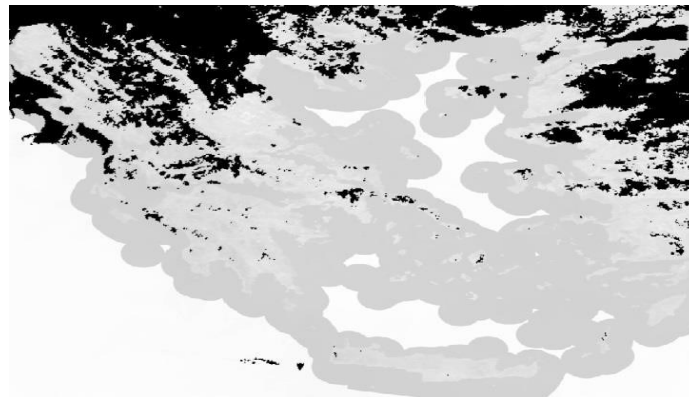
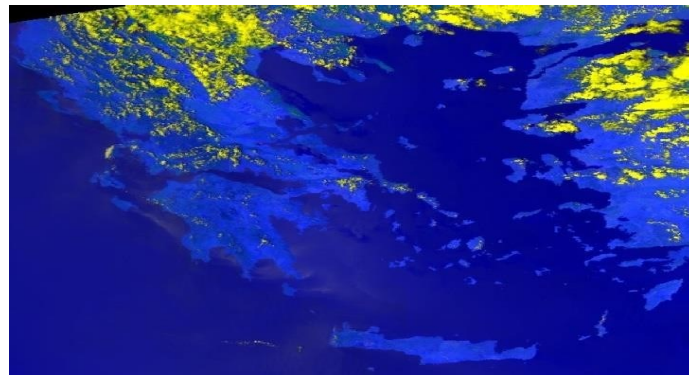


$$LSTtrend(\%) = \frac{LST(2015) - LST(1995)}{LST(1995)} 100$$

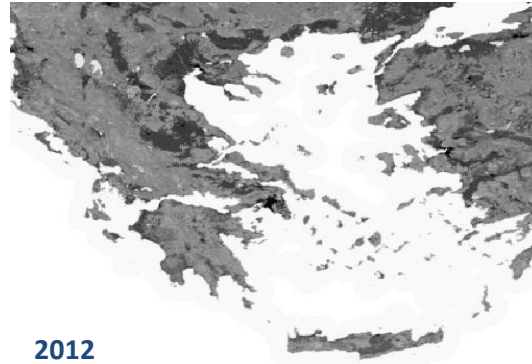
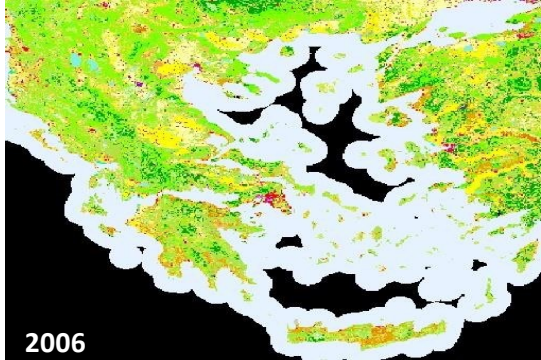
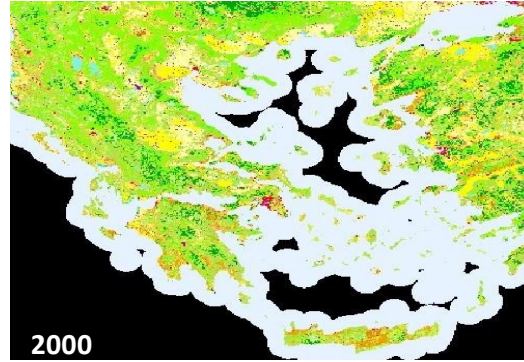
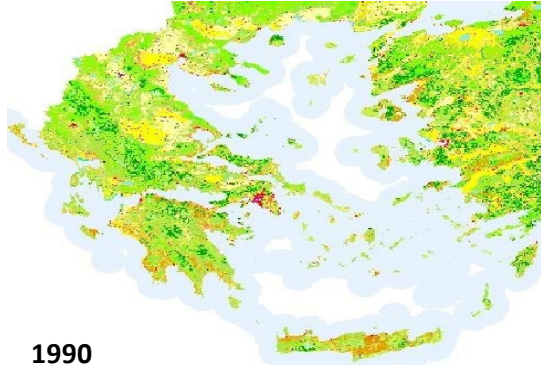
Cloud mask



NOAA-19 (2014-12 UTC)



CORINE LAND COVER



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

Area	$\Delta\epsilon$	E
Urban	-0.007	0.97
Semi-urban	-0.003	0.98
Rural	0	0.989

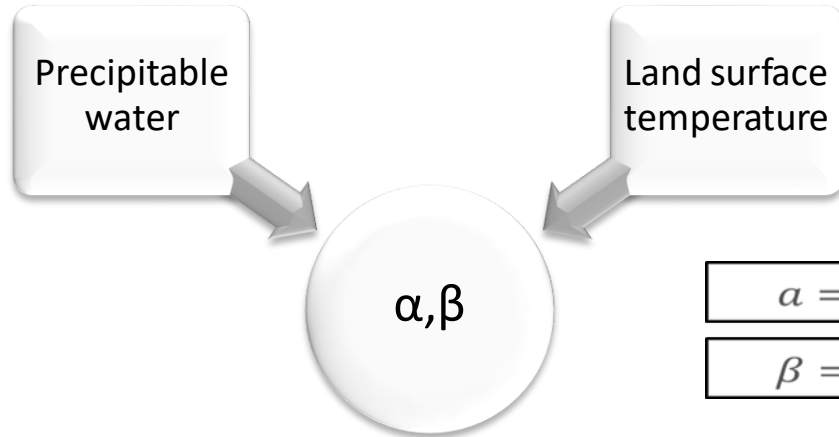
SPLIT WINDOW ALGORITHM

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

T_4 = brightness temperature channel 4

T_5 = brightness temperature channel 5

ϵ = mean spectral emissivity for channels 4 and 5

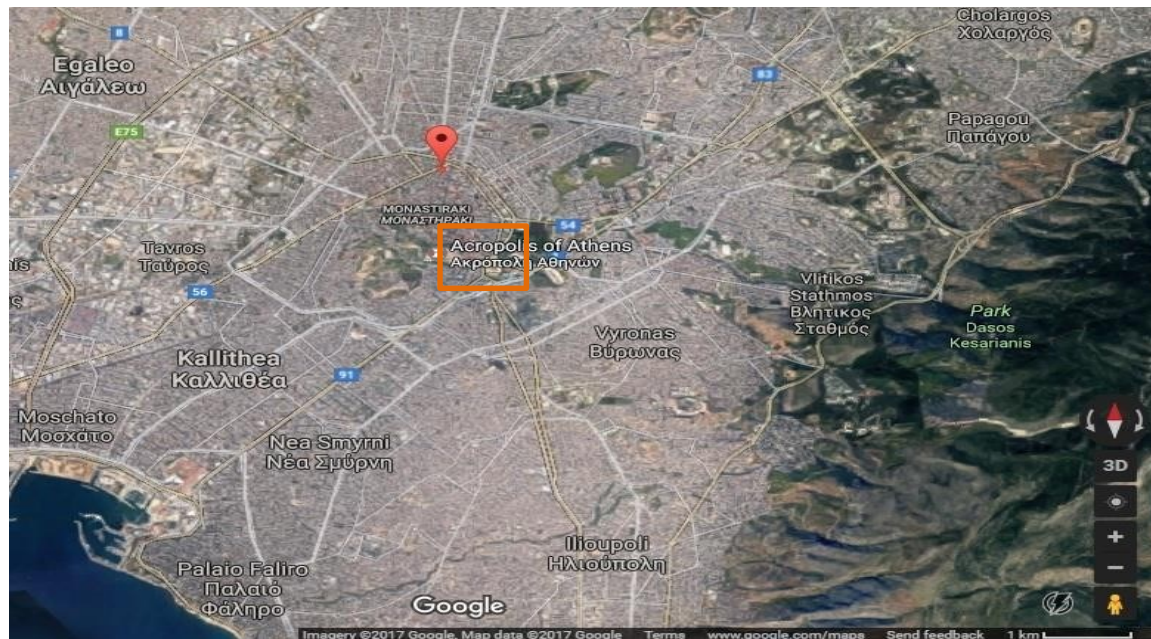
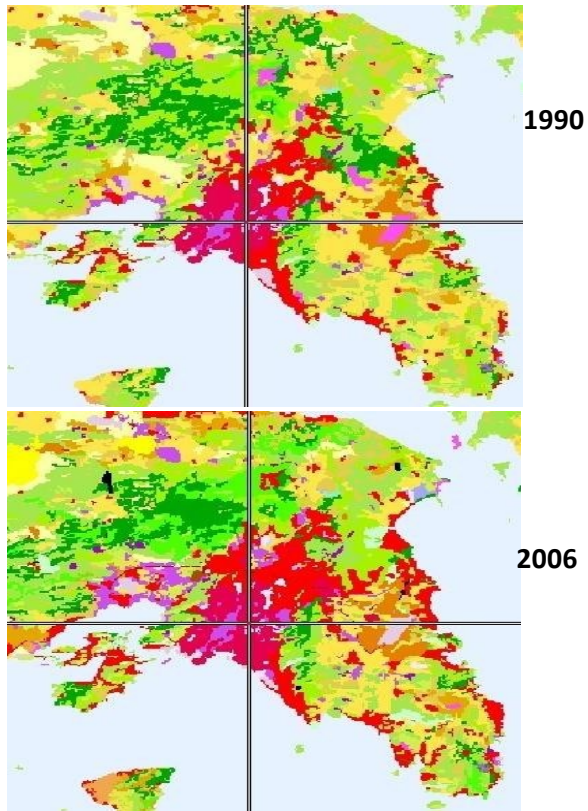


12:00 UTC	PW (gr/cm ²)
July	1.669

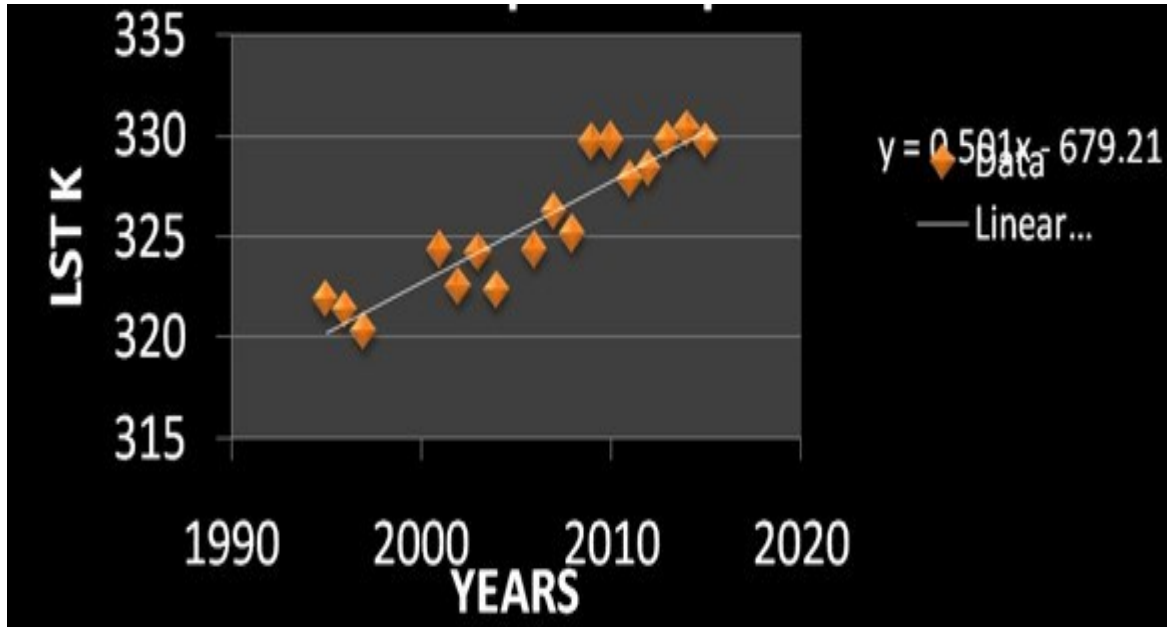
$$a = (0.190 \cdot PW - 0.103)T_4 - 67 \cdot PW + 107$$

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

Center of Athens

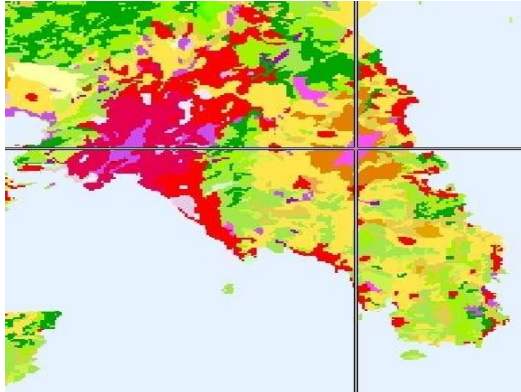


Center of Athens

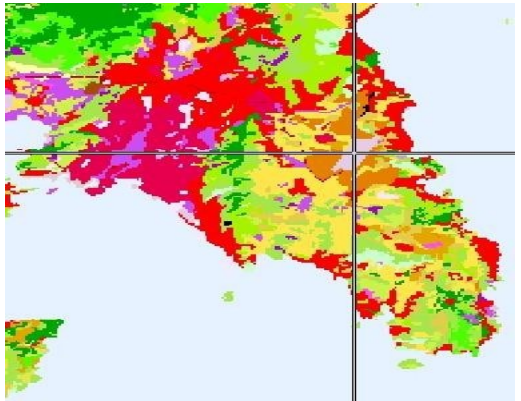


Mean value	325.763 K
Increase	10 K

Landscape change – from natural to built



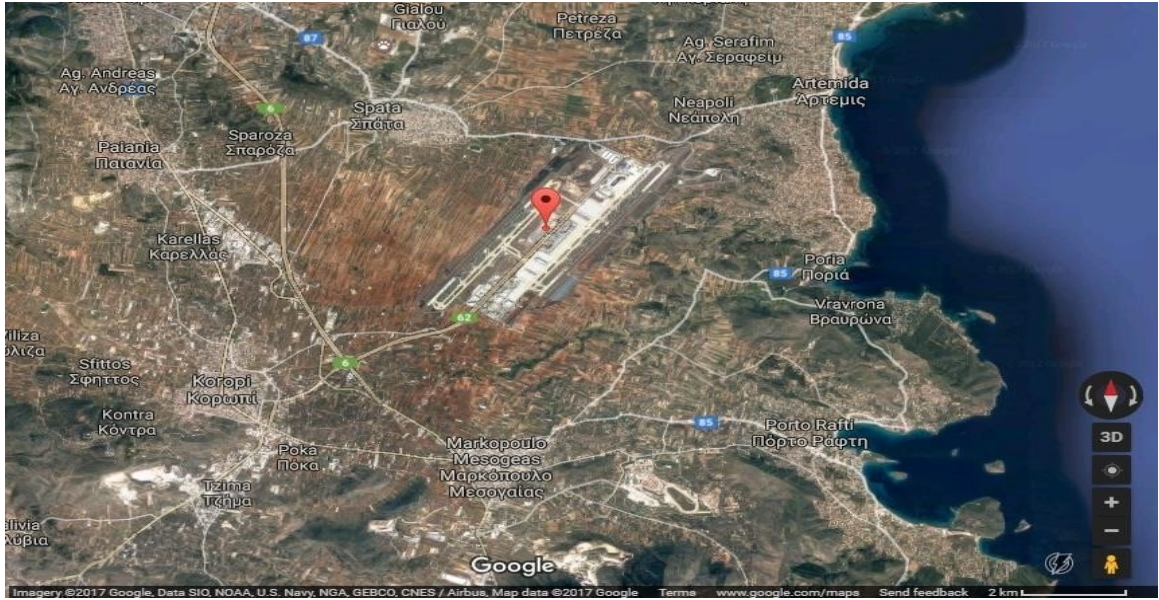
1990



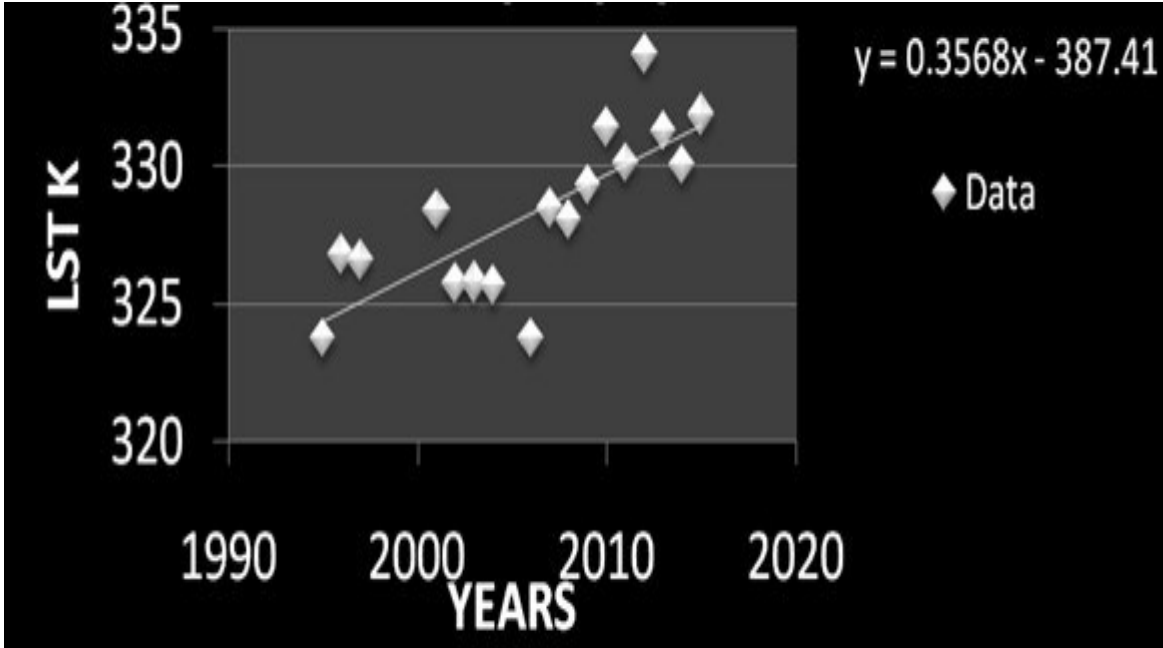
2006



Airport since 2001. Previously agricultural/rural areas

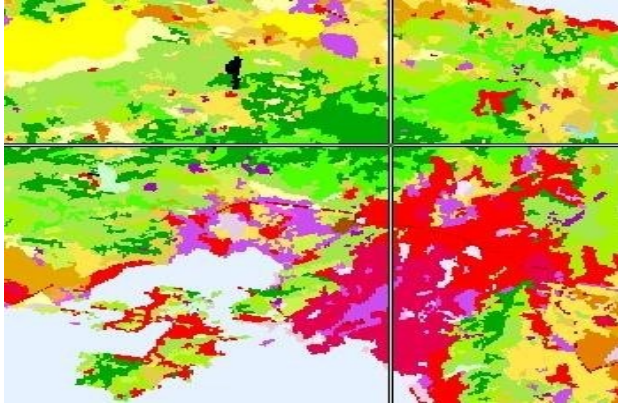


Landscape change – from natural to built



Mean value	328.320 K
Trend	2.1 %
Increase	6.8 K

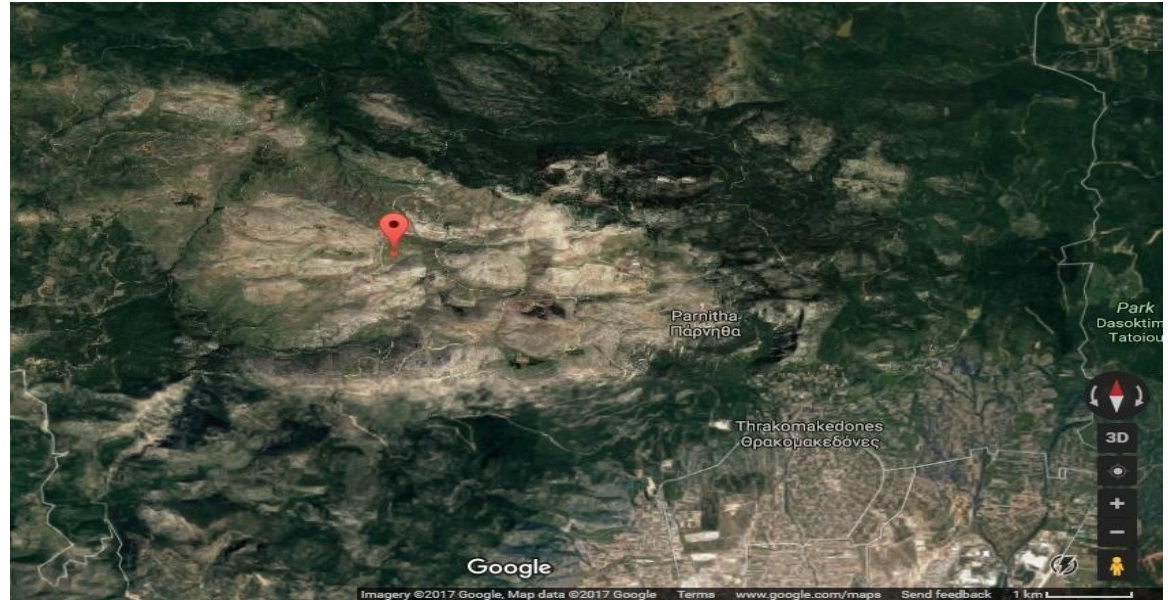
Mountainous area



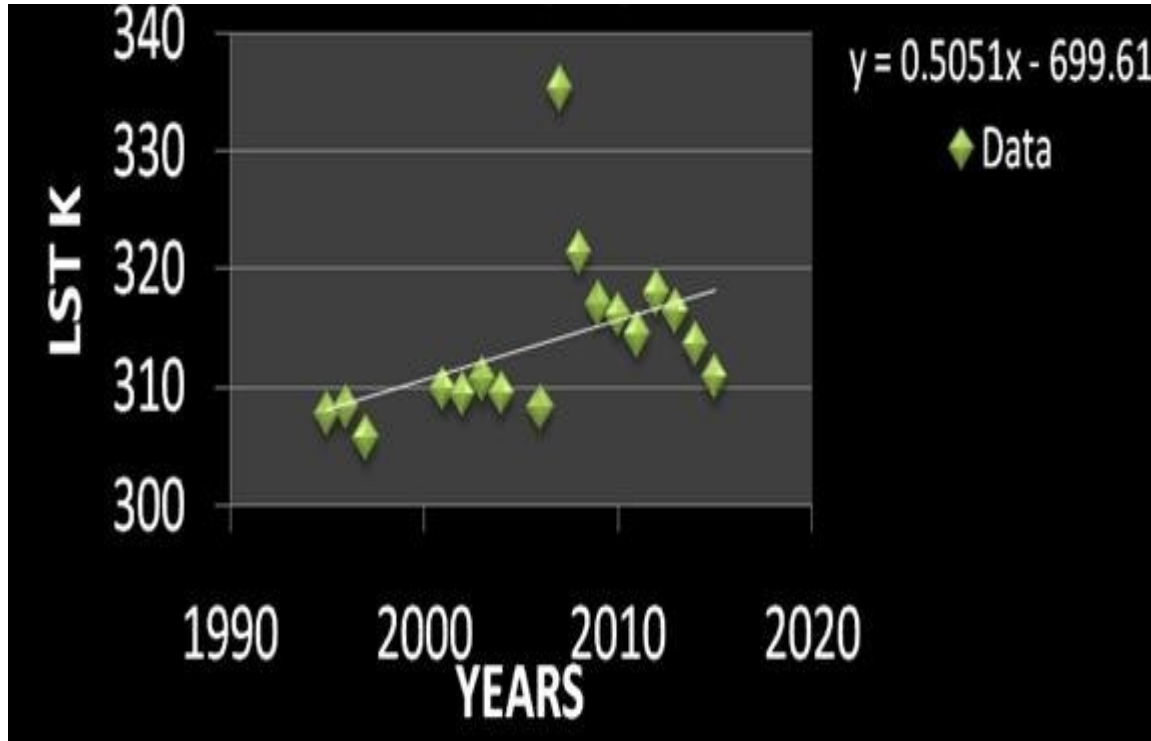
2006



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



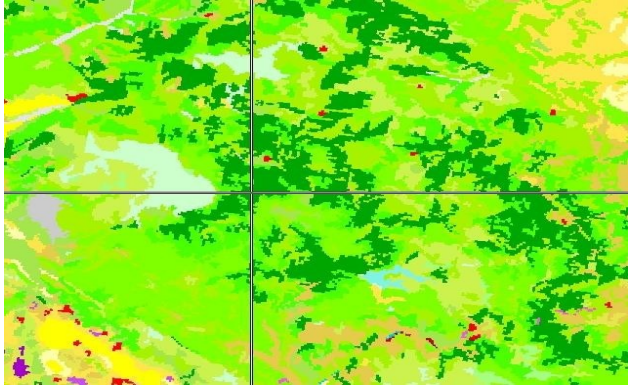
Mountainous area



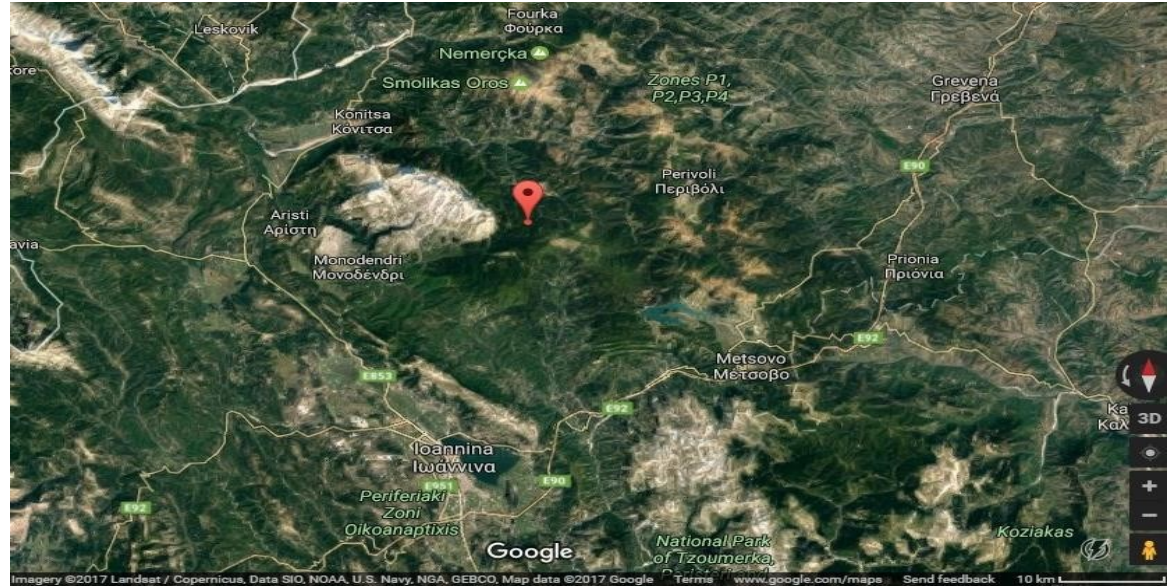
Mean value	313.694 K
Increase	10 K

Nature reserve (Natura 2000 network)

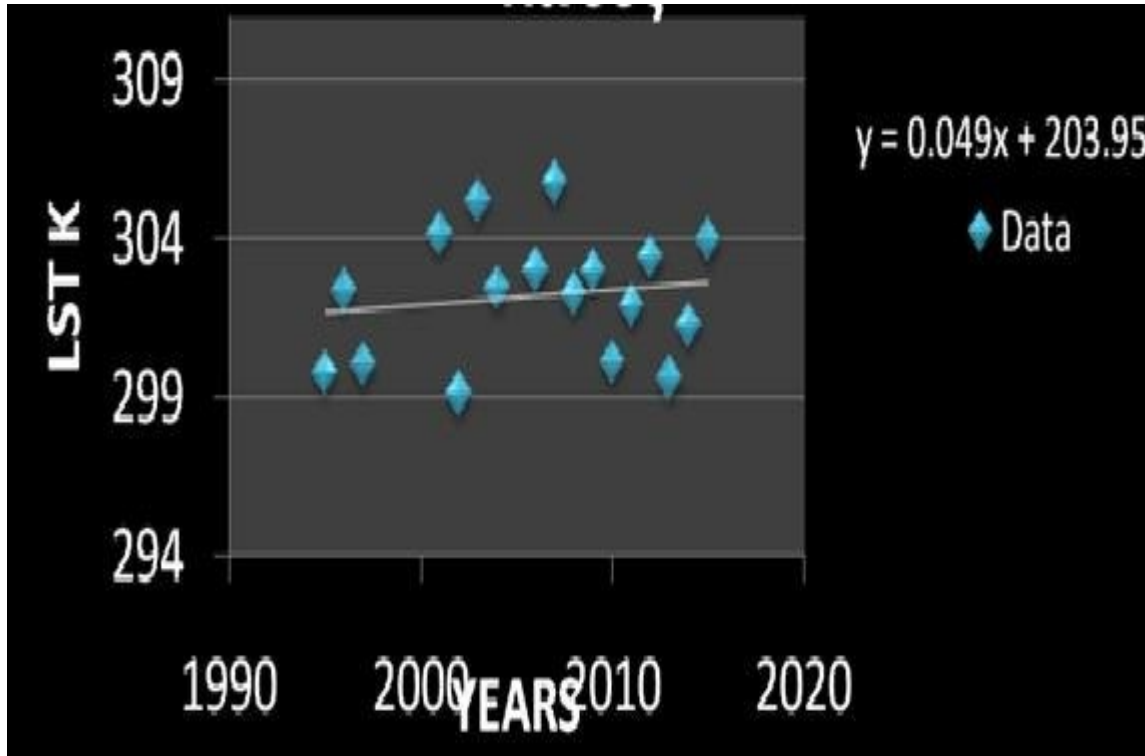
2006



- Forested area throughout the study period



Nature reserve (Natura 2000 network)



Mean value	302.224 K
Increase	0.9 K

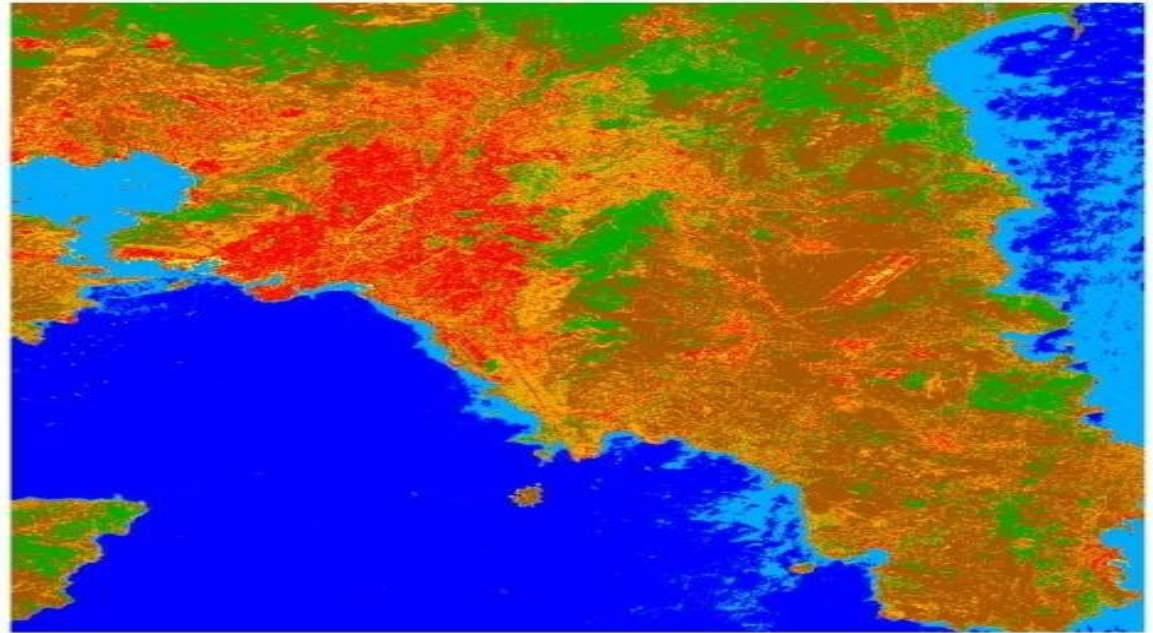
Η σημασία της χωρικής διακριτικής ικανότητας
(και του συνδυασμού φασματικών περιοχών)

CLASSIFICATION LANDSAT – 8 IMAGE

Υπόμνημα

Classification Landsat 8

- See
- Seecoast
- Urban
- Suburban
- Roads
- Vegetation
- Land



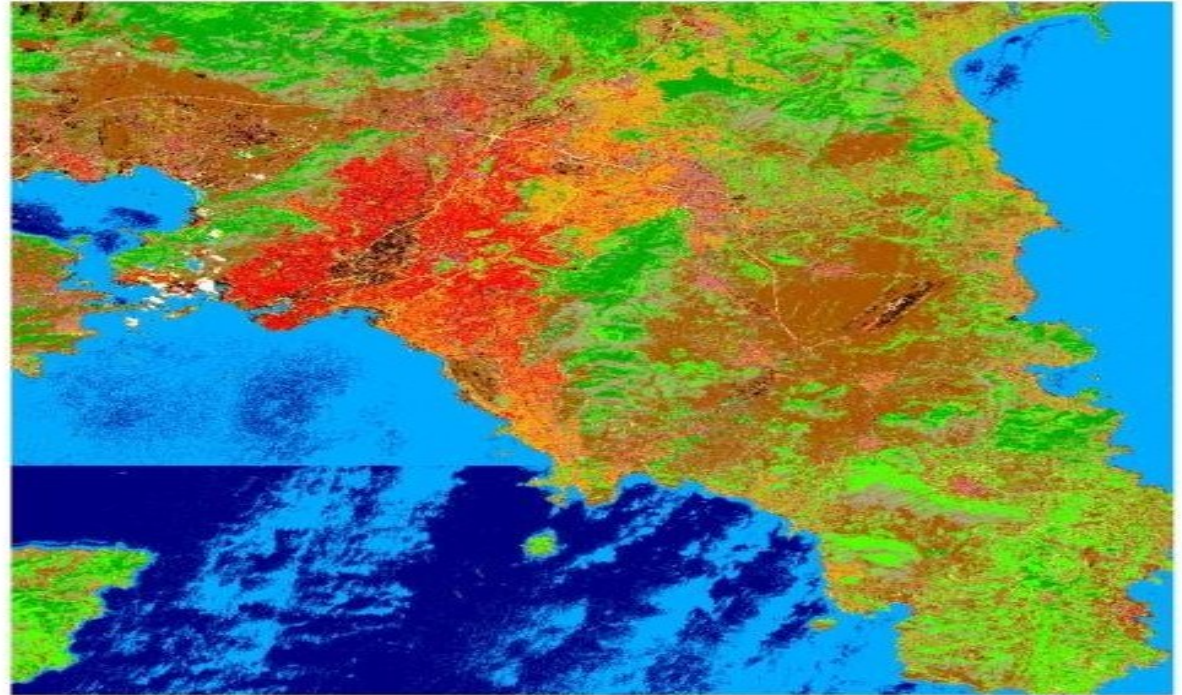
*Source for Slides 71-79, Remote Sensing and
Image Processing Unit ,Univ. of Athens, 2017
(G. Giannakogiorgos)*

CLASSIFICATION SENTINEL -2 IMAGE

Υπόμνημα

Classification Sentinel 2

- See
- Seecoast
- Vegetation
- Dense vegetation
- Urban
- Tile roofs
- Industrial zone
- Suburban
- Roads
- Agriculture
- Barren land
- Clouds



ACCURACY ASSESSMENT

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

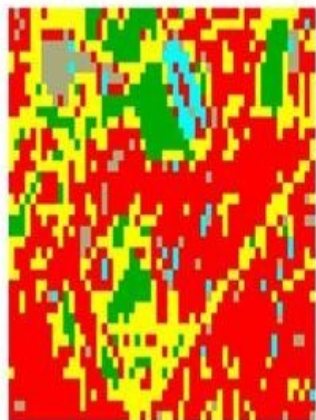
Landsat - 8 68.73%

Sentinel -2 73.82%

NON HOMOGENEOUS AREAS

Classification non homogeneous Landsat 8

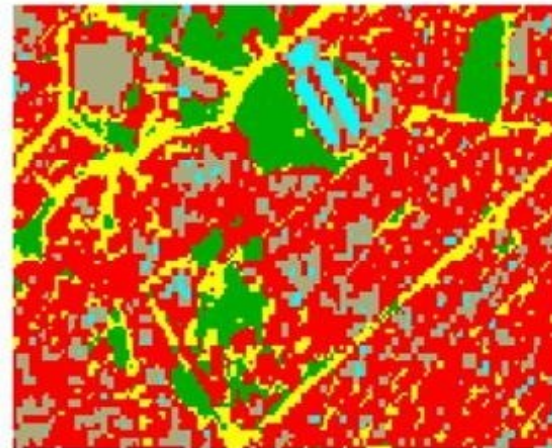
- Urban
- Kallimarmaro
- Roads
- Columns of the Temple of Olympian Zeus
- Vegetation



Υπόμνημα

Classification non homogeneous Sentinel 2

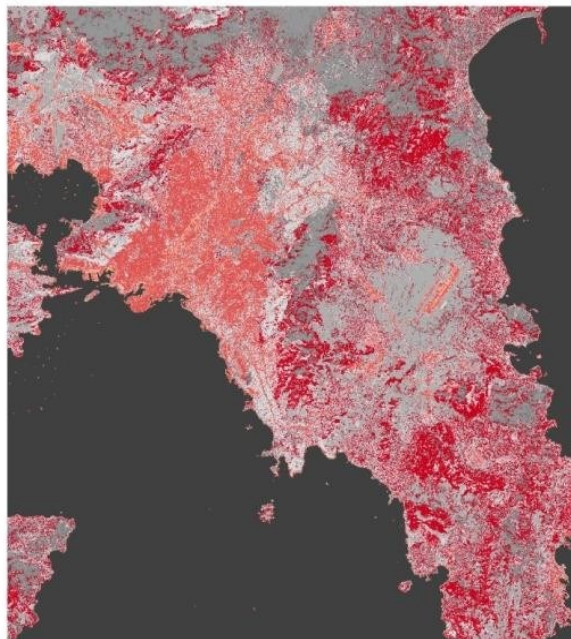
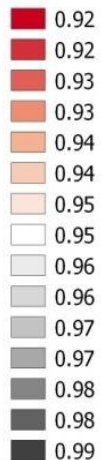
- Urban
- Kallimarmaro
- Roads
- Columns of the Temple of Olympian Zeus
- Vegetation



Συντελεστής εκπομπής με βάση το δορυφόρο LANDSAT -8 (αριστερά) και το δορυφόρο SENTINEL -2 (δεξιά) και την κάλυψη γης

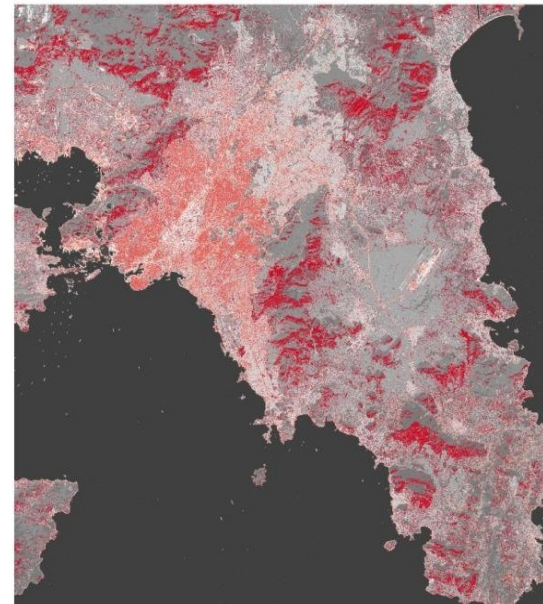
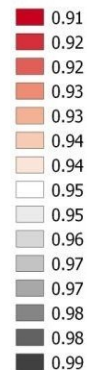
Υπόμνημα

LSE LANDSAT 8



Υπόμνημα

LSE SENTINEL 2



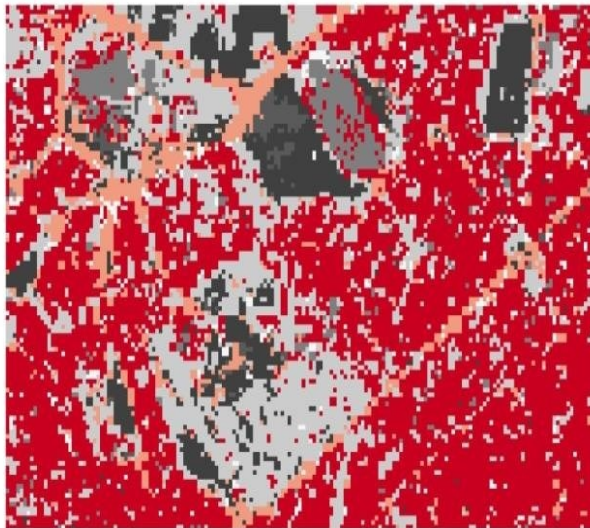
Landsat 8

Sentinel 2

LSE: NON HOMOGENEOUS AREAS

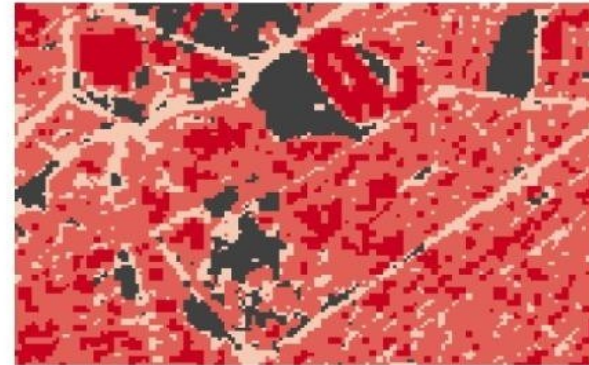
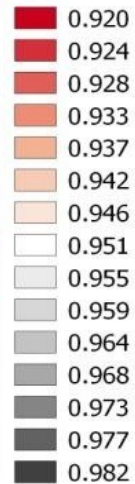
Υπόμνημα

LSE non homogeneous Landsat 8



Υπόμνημα

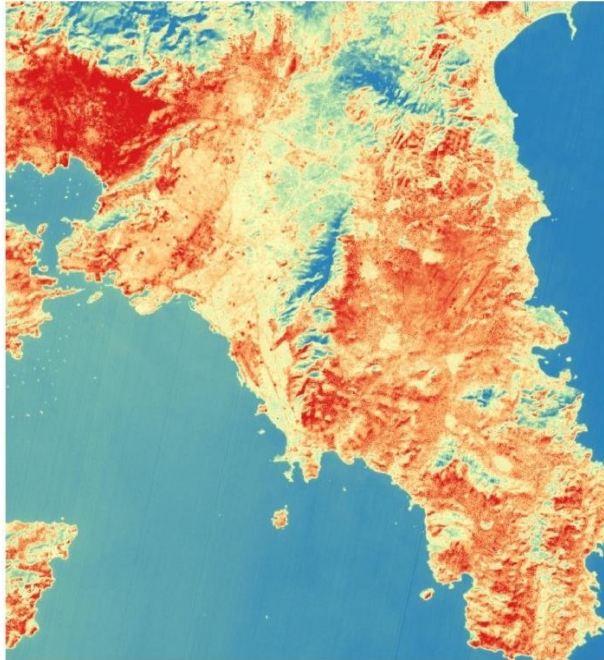
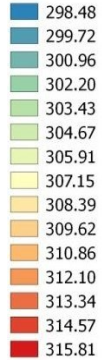
LSE non homogeneous Sentinel 2



Επιφανειακή θερμοκρασία εδάφους από LANDSAT – 8 (αριστερά) και SENTINEL – 2 (δεξιά)

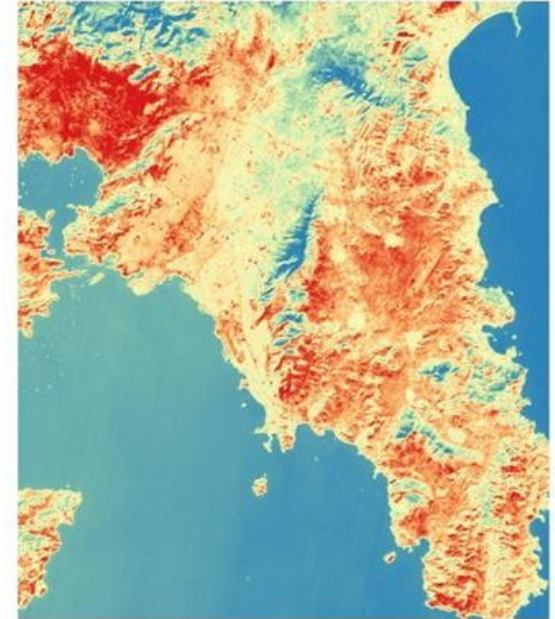
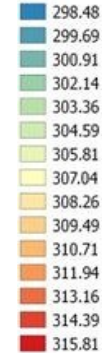
Υπόμνημα

LST LANDSAT 8



Υπόμνημα

LST SENTINEL 2



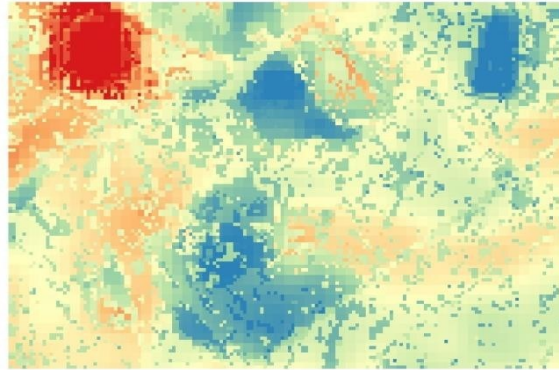
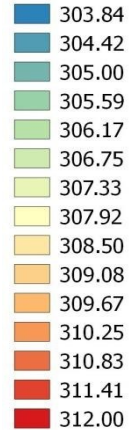
with land cover from Landsat 8

with land cover from Sentinel 2

LST: NON HOMOGENEOUS AREAS

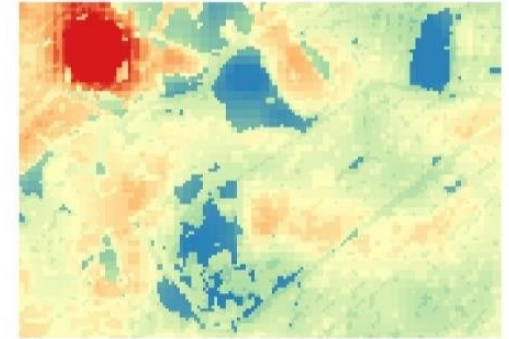
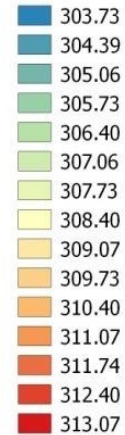
Υπόμνημα

LST non homogeneous Landsat 8



Υπόμνημα

LST non homogeneous Sentinel 2



COMPARISON OF AIR TEMPERATURE AS EXTRACTED FROM LST

$$(T_a = 1.2104T_s - 17.676)$$

(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