Practical on the Thermal Environment in urban areas

(with emphasis to the Urban Heat Island)

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Exercise

A. Assessing the thermal environment in Athens and Budapest using satellite images with special emphasis given to the surface urban heat island (UHI)

This exercise is a step-by-step guide for the estimation of Land Surface Temperature (LST) using the SNAP toolbox as well as Landsat 8 and Sentinel 3 images acquired over Athens (Greece) and Budapest (Hungary). Thermal infrared bands are particularly useful for assessing the temperature difference between the city and the surrounding rural areas, thus assessing the urban heat island phenomenon. The Sea and Land Surface Temperature Radiometer (SLSTR) on board Sentinel 3 covers 9 spectral bands (550–12 000 nm), with swath widths of 1420 km (nadir) and 750 km (backwards). The Landsat 8 Thermal Infrared Sensor (TIRS) provides two adjacent thermal bands (10.6-11.19 and 11.5-12.51 μm).

Like many metropolitan areas, Athens and Budapest are affected by an Urban Heat Island (UHI), which is caused by the large urban areas becoming warmer than the natural rural areas. In several cases, the intensity of UHI reaches 4-6 degrees Celsius, whereas intensities of the order of 12 degrees Celsius have been also observed. By its nature, concrete, asphalt and buildings found in urban areas tend to absorb heat, and a lack of trees as well as other plant life prevents natural cooling from occurring.

It should be mentioned that in terms of the use of TIRS data, a single channel algorithm for the LST estimation is applied as based to band 10 of Landsat 8. Although there is a second thermal infrared band (band 11), the use of a split-window algorithm is not recommended yet due to the calibration uncertainty associated with Band 11 (from http://landsat.usgs.gov/calibration_notices.php). More info about LST retrieval methods for Landsat 8 can be found in [1].

Calculation steps

1) Locate the exercise data in your PC (freely available from the U.S. Geological Survey: http://earthexplorer.usgs.gov/).

- **C:\....\Data**

The data consists of two folders, one for Athens and one for Budapest.

- **C:\....\Data\Athens**
- **C:\....\Data\Budapest**

2) Open the SNAP Toolbox and import the Landsat 8 data (choose either Athens or Budapest) (Figure 1).

- **File→ Import→ Optical Sensors→ Landsat→ Landsat (Geotiff)**

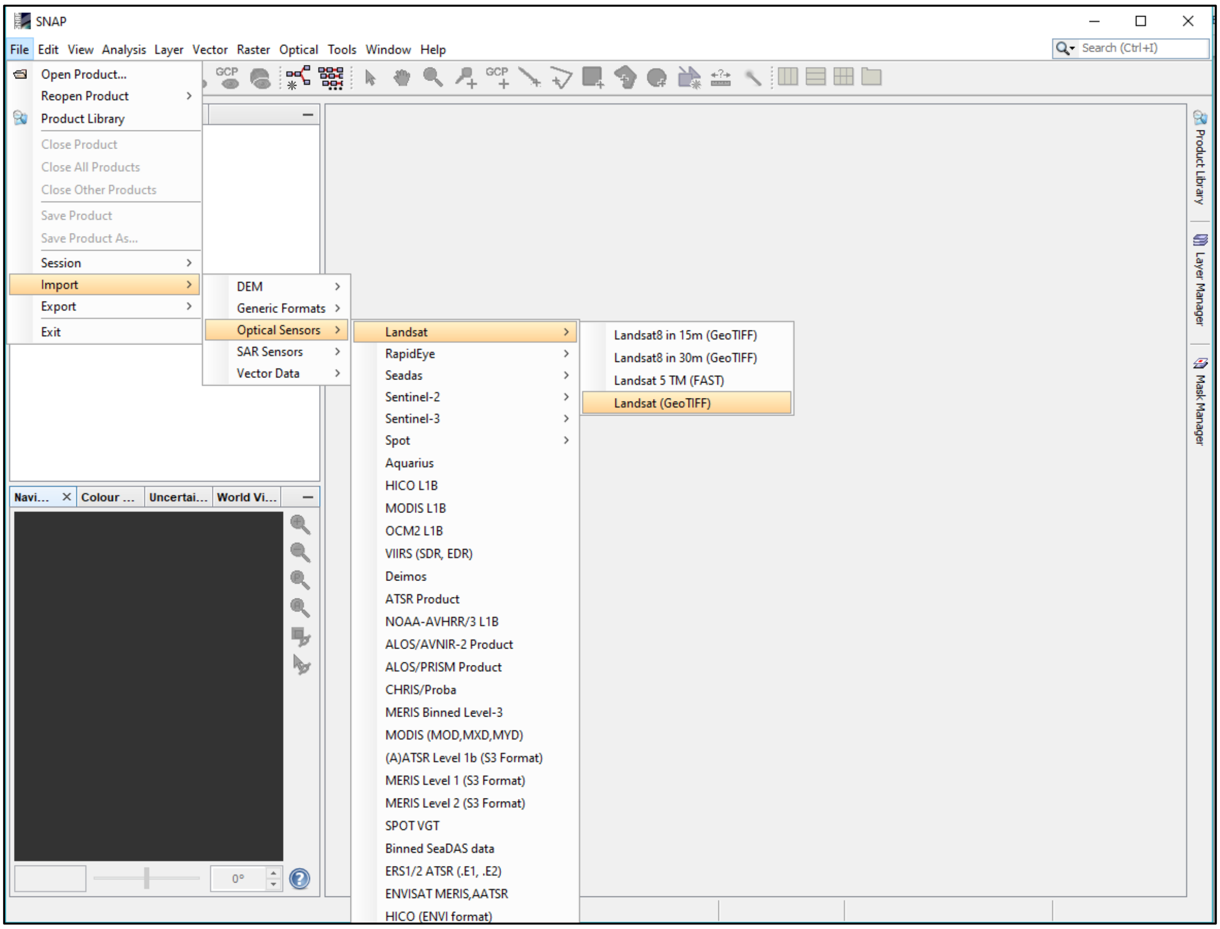

Figure 1

- Select the ….MTL.txt file in the Athens or Budapest folder and click on "**Import Product**" in the dialog box (Figure 2).

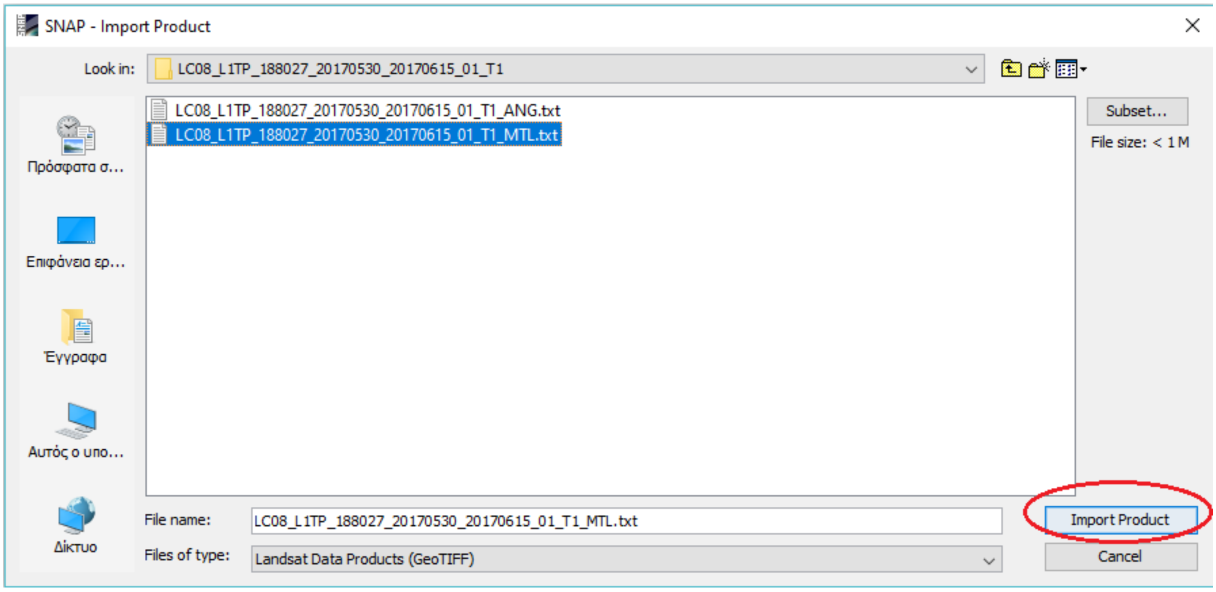

Figure 2

- Now you have imported your data to SNAP toolbox. In the “Product Explorer” window (Figure 3) you can see the metadata files and the bands. Familiarize yourself with the toolbox. Double click on any band to open the image data.

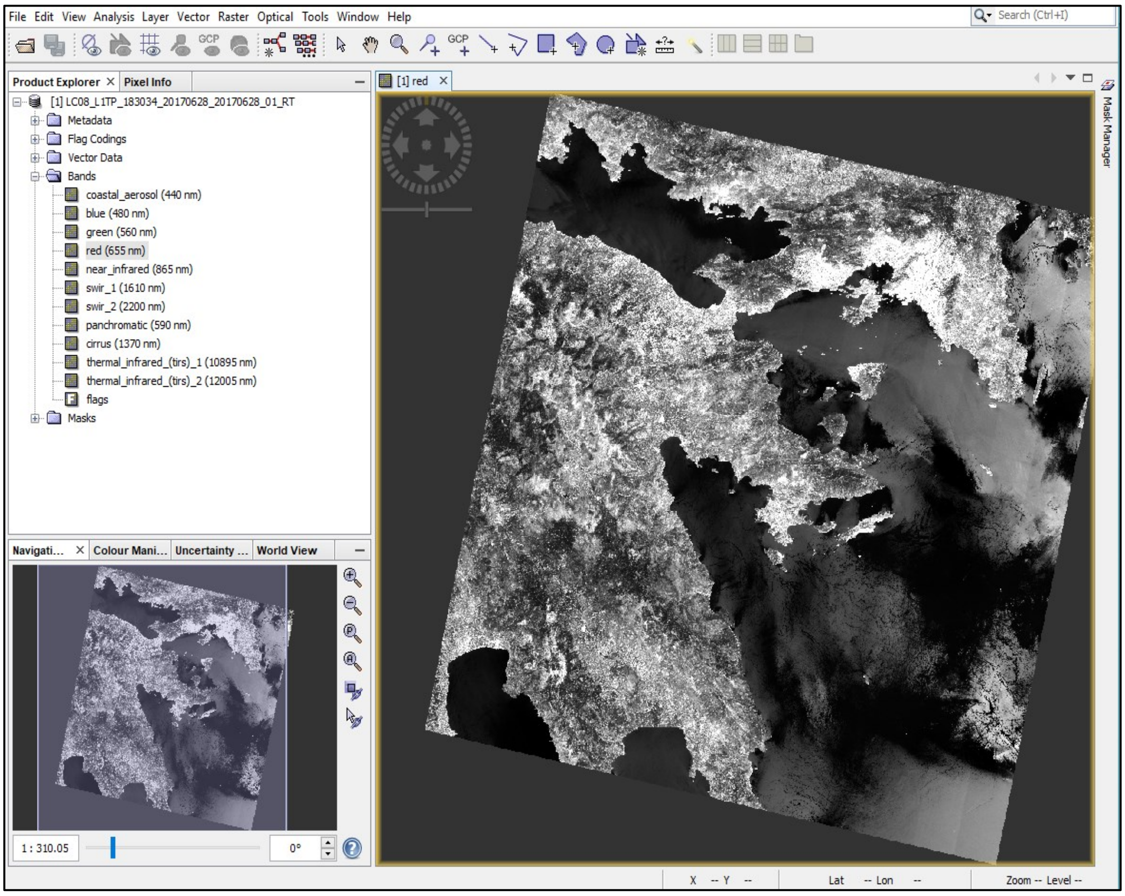

Figure 3

3) Calculation of Normalized Difference Vegetation Index (NDVI)

The vegetation density can be detected using the reflection values from the red band (Band 4) and the infrared band (Band 5). Green vegetation reflects more energy in the near- infrared band than in the visible range. Vegetation absorbs more radiation from the red band for the photosynthesis process. Leaves reflect less in the near-infrared region when they are stressed, diseased or dead. Features like clouds, water and snow show better reflection in the visible range then the near-infrared range, while the difference is almost zero for rock and bare soil. Values close to zero represent rock and bare soil and negative values represent water, snow and clouds. Taking ratio or difference of two bands makes the vegetation growth signal differentiated from the background signal.

$$\boldsymbol{NDVI} = \frac{(\boldsymbol{NIR} - \boldsymbol{RED})}{(\boldsymbol{NIR} + \boldsymbol{RED})}$$

The SNAP toolbox automatically converts the Digital Numbers (DN) from the raw Landsat 8 data to the physical measure of Top of Atmosphere (TOA) radiance (L_λ). To calculate NDVI we have to convert radiance to reflectance.

Conversion TOA radiance to reflectance for Band 4 (RED) and band 5 (NIR) & simple Atmospheric Correction

Calculate the at-surface reflectivity with the following equation:

$$\rho_\lambda=[\pi\cdot(L_\lambda - L_p)\cdot d^2 / (ESUN_\lambda\cdot\cos\theta_s)$$

where:

ρ_λ = the surface reflectance, which is "the ratio of reflected versus total power energy"

L_λ = Spectral radiance

L_p= the path radiance

d = Earth-Sun distance in astronomical units (provided with Landsat 8 metadata)

$ESUN_\lambda$ = Mean solar exo-atmospheric irradiances

$ESUN_\lambda= \pi\cdot d^2\cdot$RADIANCE_MAXIMUM / REFLECTANCE_MAXIMUM

θ_s = Solar zenith angle in degrees, which is equal to θs = 90° - θe where θe is the Sun elevation (provided with Landsat 8 metadata)

The path radiance L_p is the radiance resulted from the interaction of the electromagnetic radiance with the atmospheric components and it can be calculated with the following equation:

$$L_p= L_{min} - [0.01\cdot ESUN_\lambda\cdot\cos\theta_s/(\pi\cdot d^2)]$$

Where L_{min} is the minimum radiance and it can be estimated from the histogram. (Figure 8).

- Open the metadata file (e.g. OPEN ATTRIBUTES, MIN – MAX_RADIANCE, MIN-MAX_REFLECTANCE, etc.) to find the data you need: d, θ_e, RADIANCE_MAXIMUM, REFLECTANCE_MAXIMUM (Figure 4). To calculate L_{min} open the near_infrared band and select the tab **Analysis→Histogram** (Figure 5). Click on the refresh button, wait for the histogram to appear and finally zoom in the left-down corner of the histogram, by pressing left click while drawing a square over the preferred area, in order to estimate the value for L_{min} (Figure 6). Repeat this step to find the L_{min} for the red band.

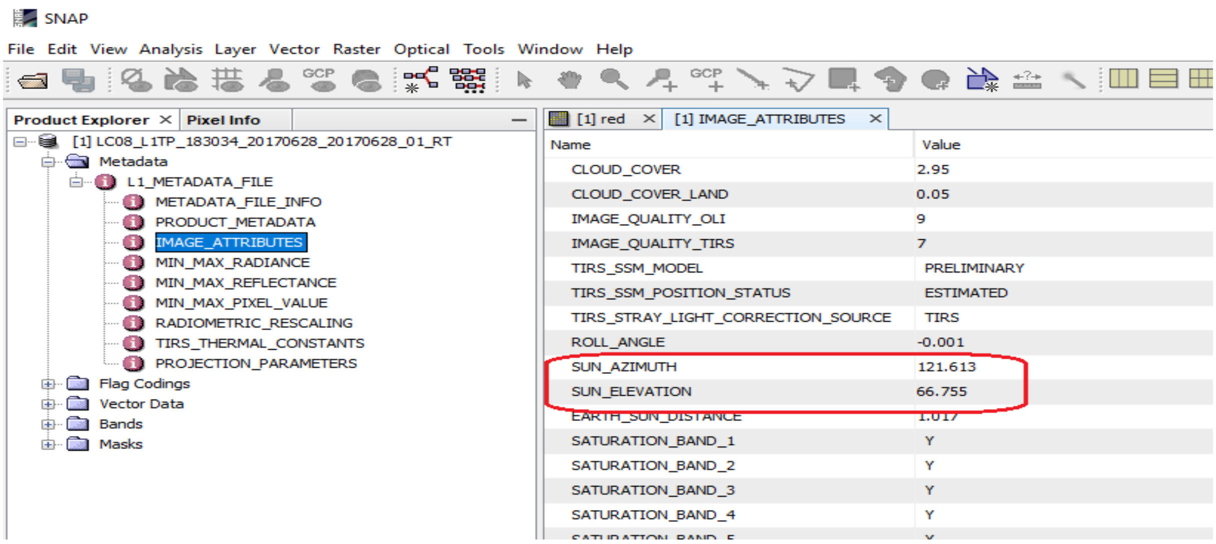

Figure 4

Make sure you click on the refresh button to calculate the histogram

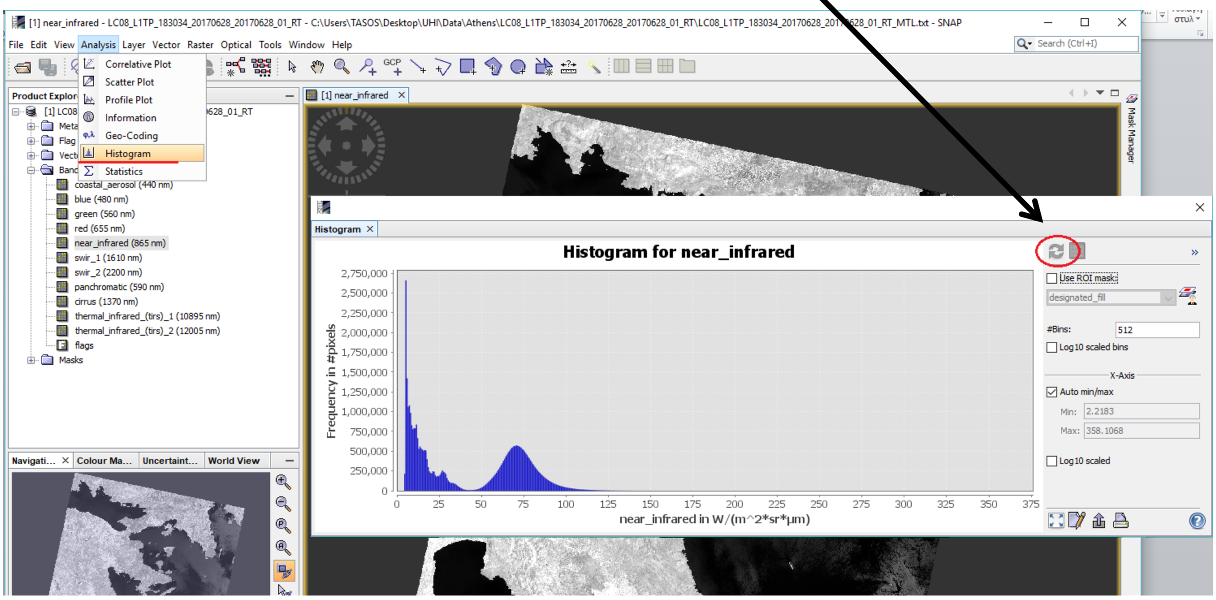

Figure 5

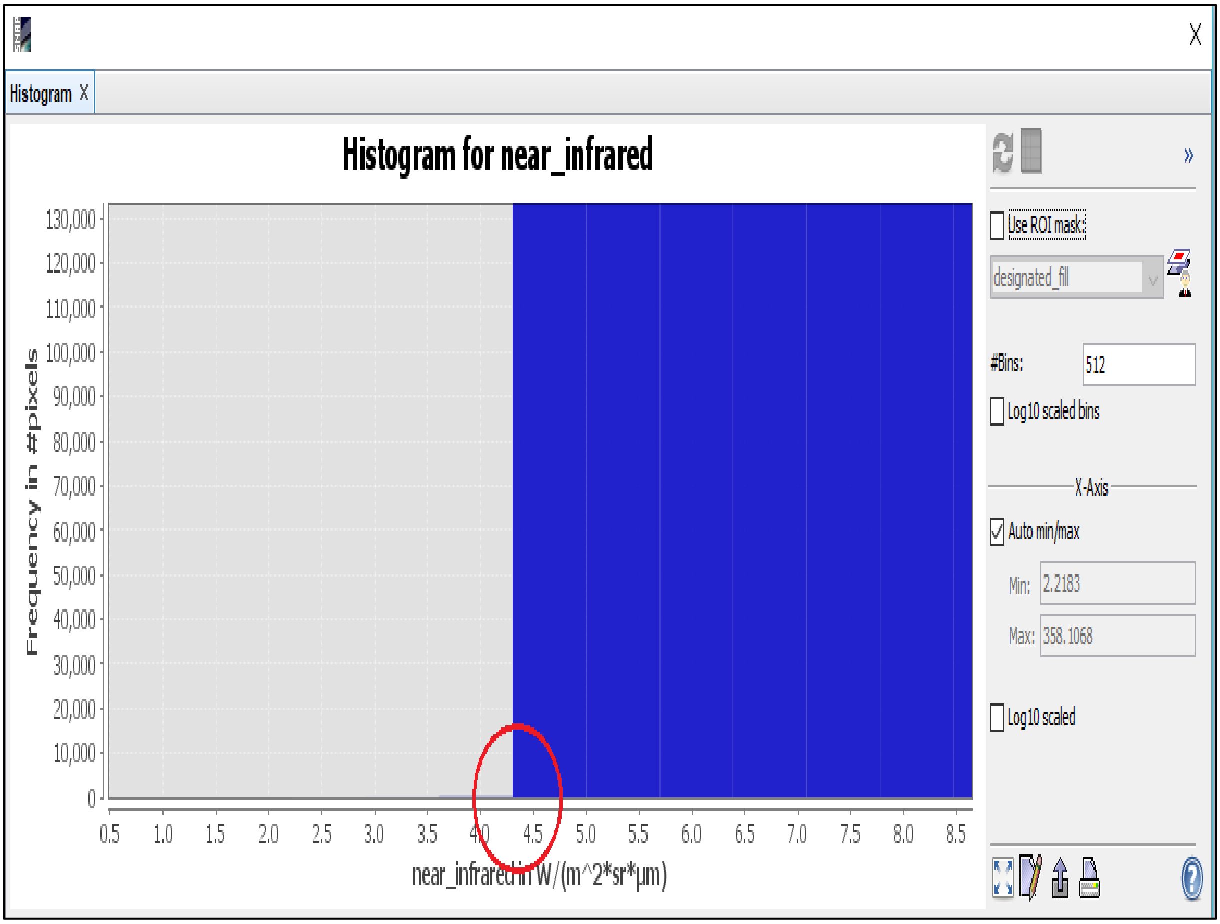

Figure 6

- Fill out the table for Budapest

	Athens		Budapest	
d	1.017			
θ_e	66.755			
θ_s=90-θ_e	23.245			
cosθs	0.9188			
RADIANCE_MAX	Band 4: 585.192	Band 5: 358.108	Band 4:	Band 5:
REFLECTANCE _MAX	Band 4: 1.211	Band 5: 1.211	Band 4:	Band 5:
$ESUN_\lambda$	Band 4:1570.16	Band 5: 960.86	Band 4:	Band 5:
L_{min}	Band 4: 13.75	Band 5: 4.3	Band 4:	Band 5:
L_p	Band 4: 9.31	Band 5: 1.583	Band 4:	Band 5:

- Next we will calculate the reflectance for Band 4 (Name the file refl_red). Select **Raster→ Band maths…→ Edit Expression…** (Figure 7). Be careful to uncheck the **Virtual** box.

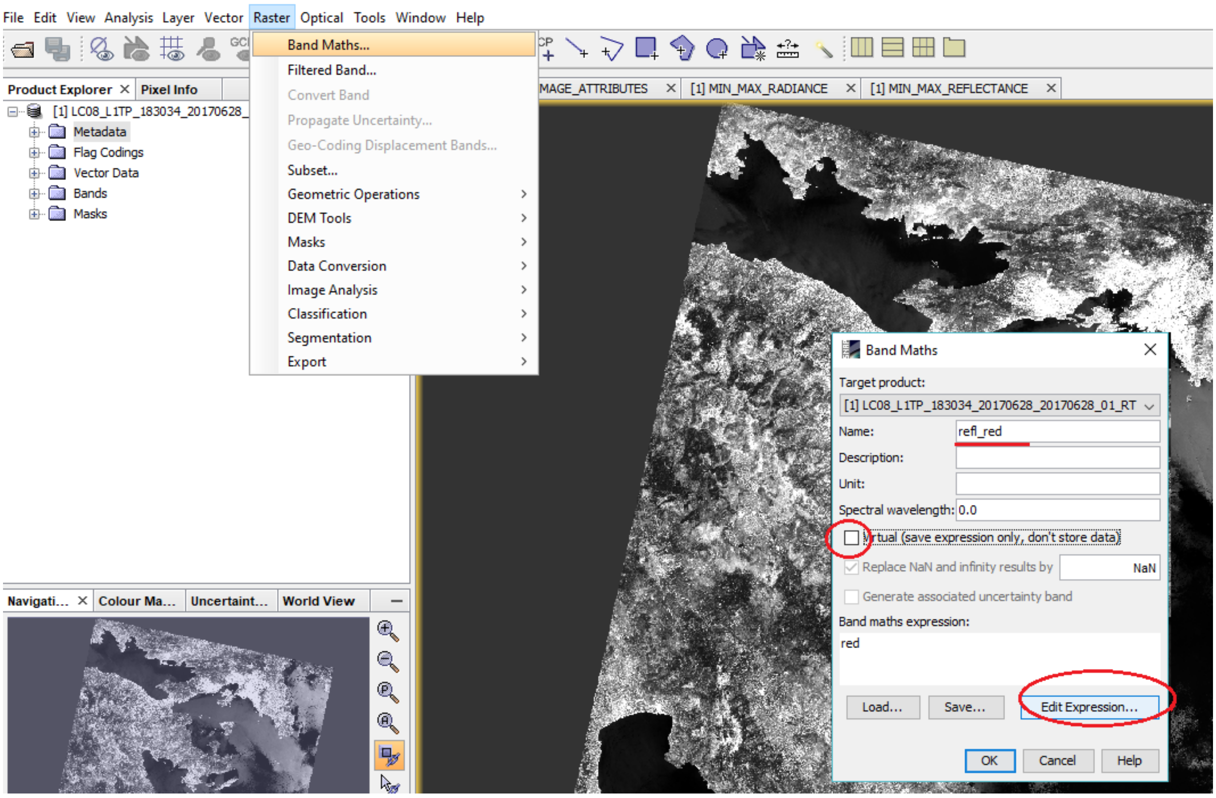

Figure 7

- Create the equation **$refl\_red=[\pi\cdot(L_{red} - L_p)\cdot d^2 / (ESUN_\lambda\cdot\cos\theta_s)$** in the **Band maths Expression Editor** (Figure 8).

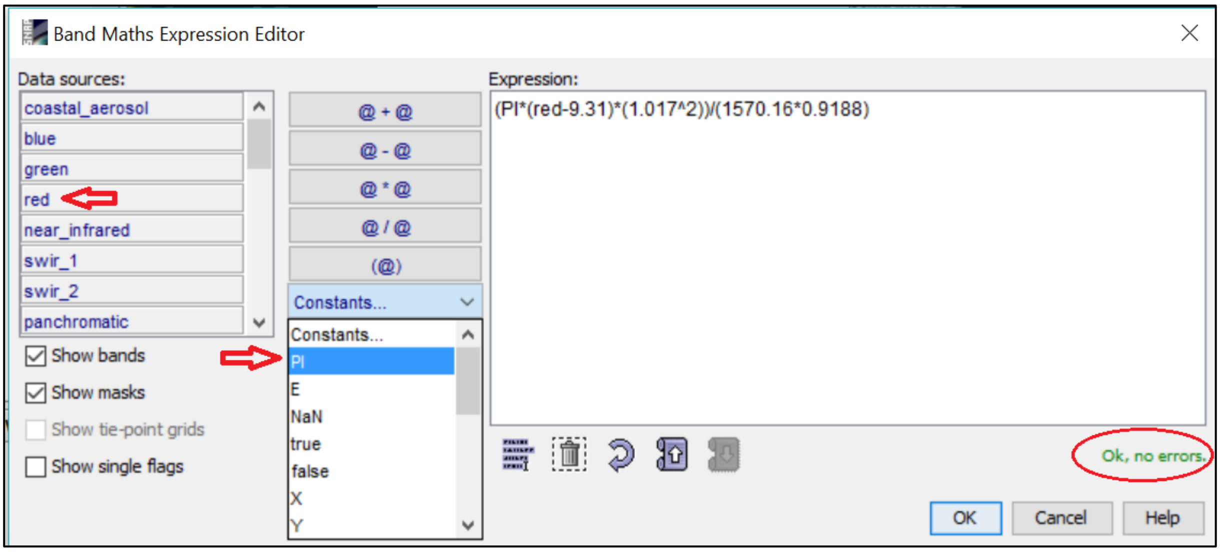

Figure 8

- Repeat the above step (using **Bands maths)** to calculate the reflectance for band 5 (name it refl_nir) and then calculate NDVI (using Band maths again) (Figure 9)

[Use the following equations: **$refl\_nir=[\pi\cdot(L_{nir} - L_p)\cdot d^2 / (ESUN_\lambda\cdot\cos\theta_s)$** and $\boldsymbol{NDVI} = \frac{\boldsymbol{refl\_nir - refl\_red}}{\boldsymbol{refl\_nir+refl\_red}}$]

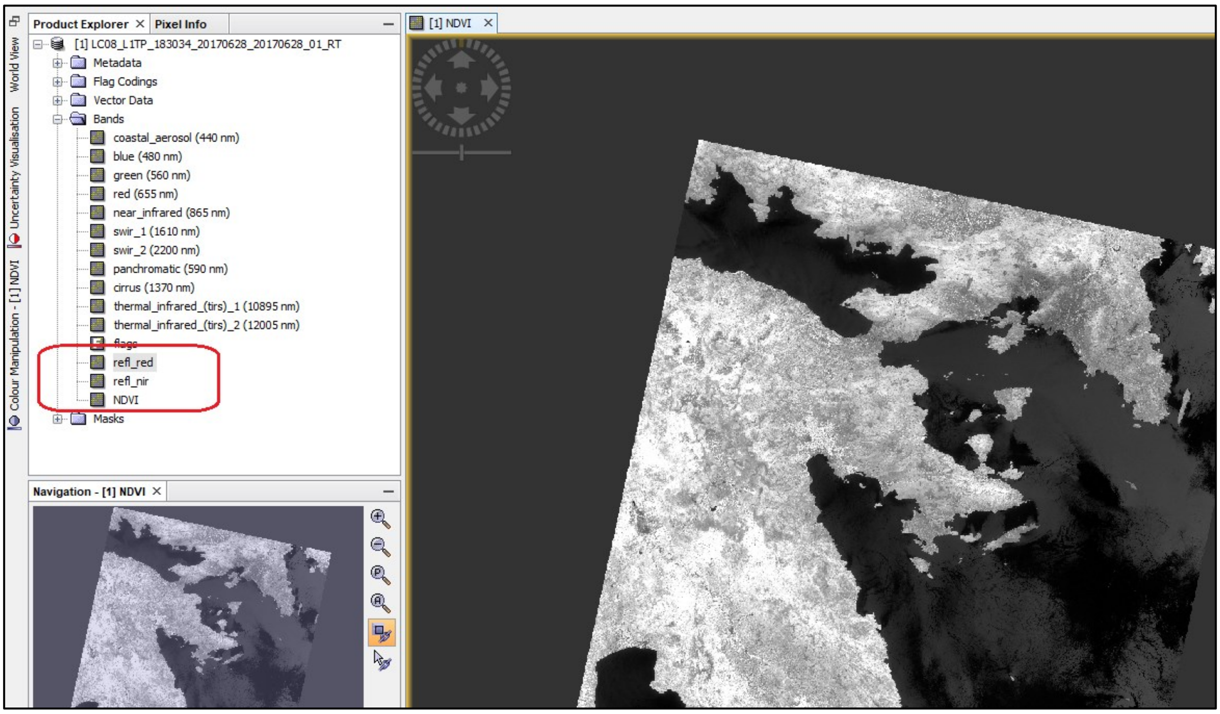

Figure 9

4) Use NDVI to estimate Land Surface Emissivity (LSE)

We will use certain NDVI values (NDVI thresholds method from [2]) to distinguish between soil pixels (NDVI < NDVIs) and pixels of full vegetation ($NDVI > NDVI_v$).

For those pixels composed of soil and vegetation (mixed pixels, $NDVI_s \leq NDVI \leq NDVI_v$), the method uses the following simplified equation:

$$\varepsilon_\lambda = \varepsilon_{v\lambda} P_V + \varepsilon_{s\lambda}(1 - P_V) + C_\lambda$$

where ε_v and ε_s are, respectively, the soil and vegetation emissivities, P_V is the proportion of vegetation and C is a term which takes into account the cavity effect due to surface roughness (C = 0 for flat surfaces). P_v can be obtained from NDVI using the following equation

$$P_v = [(NDVI - NDVI_s) / (NDVI_v\text{-}NDVI_s)]^2$$

Values of $NDVI_v = 0.5$ *and* $NDVI_s = 0.2$ will be used in this exercise. In order to obtain consistent values we set the NDVI value to 0.2 for all pixels with NDVI<0.2 and to 0.5 for all pixels with NDVI>0.5.

LSE will be calculated using the following equations

i. For $NDVI \leq 0.2$: $LSE_s = 0.98 - 0.042 \cdot refl\_red$

ii. For $0.2 < NDVI < 0.5$: $LSE_{mixed} = 0.971 \cdot (1 - P_v) + 0.987 \cdot P_v$

iii. For $NDVI \geq 0.5$: $LSE_v = 0.99$

- Use the **Band Maths** to create the new NDVI image (you will need a two steps procedure)
    - Create NDVI_2 image by setting the NDVI values to 0.2 for all pixels with NDVI<0.2 (Figure 10)

    [Select the “Operators” option and select the “if@ then @ else @” option. Use the following expression: if NDVI<0.2 then 0.2 else NDVI]

    - Create NDVI_3 image from the NDVI_2 image by setting the NDVI value to 0.5 for all pixels with NDVI_2 >0.5

    [use the following expression: if NDVI_2>0.5 then 0.5 else NDVI]

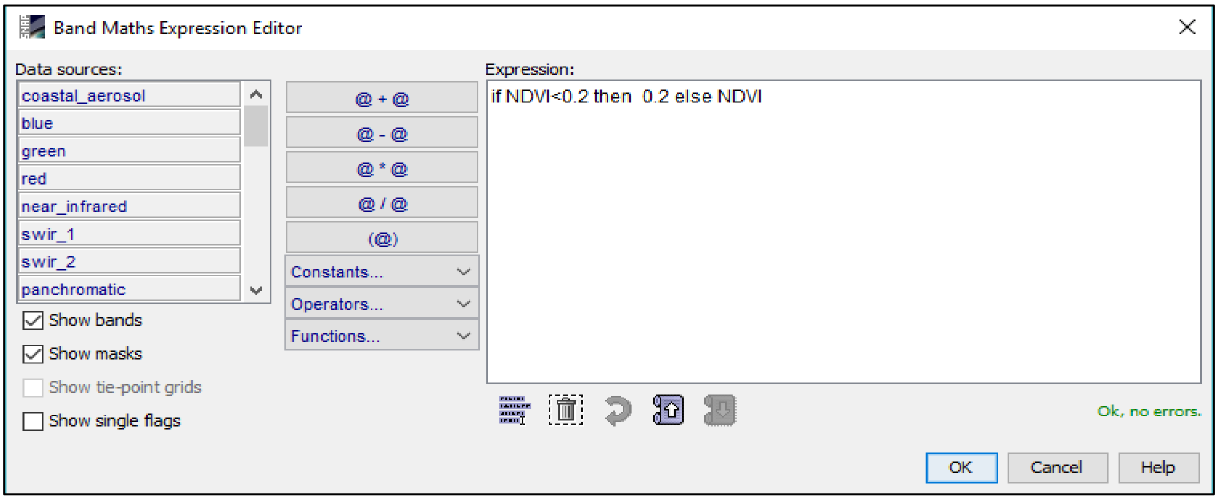

Figure 10

- Use the **Band Maths** to calculate the proportion of vegetation P_v from the NDVI_3 image (Figure 11)

[Remember that $P_v = [(NDVI - NDVI_s) / (NDVI_v\text{-}NDVI_s)]^2$, so use the following expression:
((NDVI_3-0.2)/0.3)* ((NDVI_3-0.2)/0.3)]

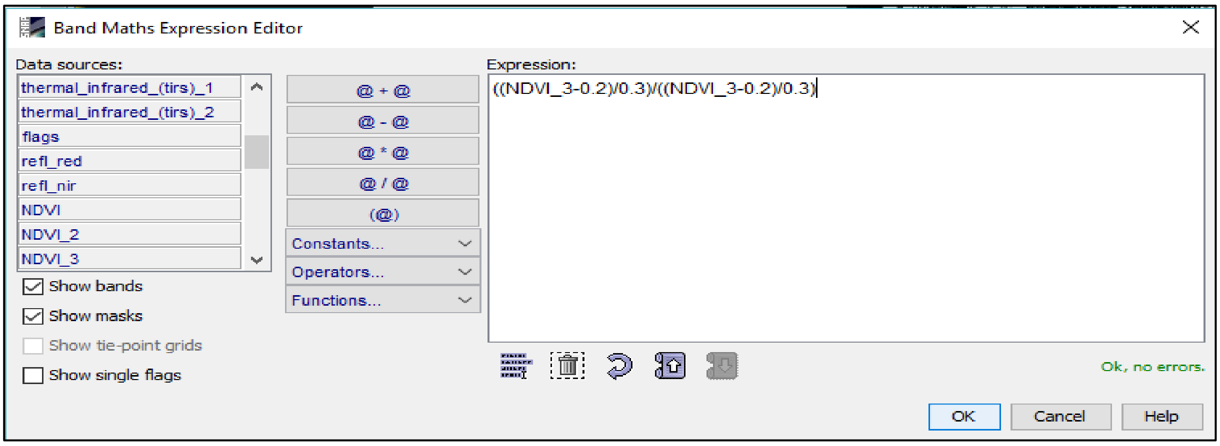

Figure 11

- Use the **Band maths** to create the Land Surface emissivity (LSE) image from the NDVI_3 image (you will need a five steps procedure) (Figure 12)

1. create LSE_s image
[use the following expression: 0.98-0.042*refl_red]

2. create LSE_{mixed} image
[use the following expression: $0.971*(1-P_v)+0.987*P_v$]

3. create LSE_1 by replacing the values of NDVI_3 <0.201 with the LSEs values (be careful to use 0.201 instead of 0.2)
[use the following expression: if NDVI_3<0.201 then LSEs else NDVI_3]

4. create LSE_2 by replacing the values of LSE_1=0.5 to 0.99
[use the following expression: if LSE_1==0.5 then 0.99 else LSE_1]

5. create LSE by replacing the values of LSE_2<0.5 to LSE_{mixed}
[use the following expression: if LSE_2<0.5 then LSEmixed else LSE_2]

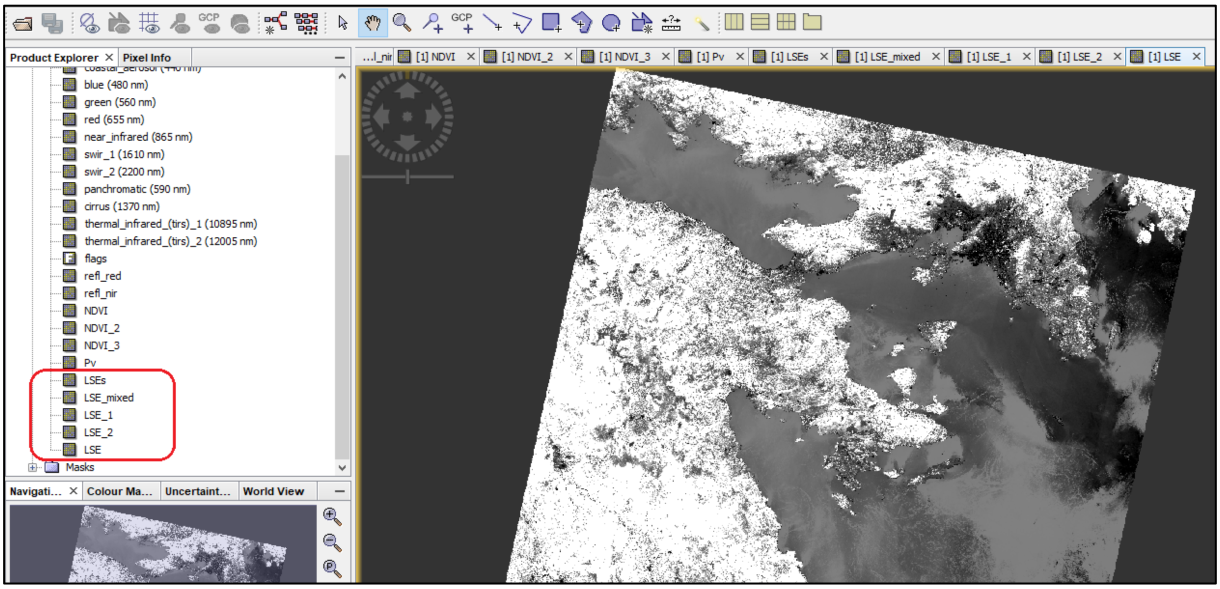

Figure 12

5) **Land surface temperature (LST) calculation**

The Single Channel algorithm developed by Jiménez-Muñoz et al. [3] retrieves land surface temperature (LST) using the following general equation:

$$LST = \gamma \cdot [1/LSE \cdot (\psi_1 \cdot L_{sen} + \psi_2) + \psi_3] + \delta$$

where LSE is the surface emissivity, and γ (gamma) and δ (delta) are two parameters given by

$$\gamma \approx \frac{T_{sen}^2}{b_\gamma L_\lambda} \qquad \delta \approx T_{sen} - \frac{T_{sen}^2}{b_\gamma}$$

where T_{sen} is the at-sensor brightness temperature of the thermal band, $b_\gamma = c_2/\lambda$ (b_γ=1324 for band 10); and ψ_1, ψ_2, and ψ_3 are the so-called atmospheric functions, given by

$$\psi_1 = \frac{1}{\tau} \qquad \psi_2 = -L_d - \frac{L_u}{\tau} \qquad \psi_3 = L_d$$

where τ is the atmospheric transmission, , L_u is the upwelling or atmospheric path radiance, L_d is the downwelling or sky radiance. These parameters can be estimated using the Atmospheric Correction Parameter Calculator which can be found in: http://atmcorr.gsfc.nasa.gov/.

Using the calculator the following results for Athens and Budapest are obtained for the dates of our data:

Athens

Date (yyyy-mm-dd): *2017-06-28*
Input Lat/Long: *37.980/ 23.730*
GMT Time: *9:04*
L8 TIRS Band 10 Spectral Response Curve
Mid-latitude summer standard atmosphere
Band average atmospheric transmission: *0.74*
Effective bandpass upwelling radiance: *2.19 W/m^2/sr/µm*
Effective bandpass downwelling radiance: *3.57 W/m^2/sr/µm*

Budapest

Date (yyyy-mm-dd): *2017-05-30*
Input Lat/Long: *47.480/19.030*
GMT Time: *9:32*
L8 TIRS Band 10 Spectral Response Curve
Mid-latitude summer standard atmosphere
Band average atmospheric transmission: 0.73
Effective bandpass upwelling radiance: 2.08 W/m^2/sr/µm
Effective bandpass downwelling radiance: 3.40 W/m^2/sr/µm

The table below provides the ψ_1, ψ_2 and ψ_3 values (use them in your calculations):

	Athens	Budapest
τ	0.74	0.73
L_u	2.19	2.08
L_d	3.57	3.40
Ψ_1	**1.3513**	**1.3698**
Ψ_2	**-6.53**	**-6.25**
Ψ_3	**3.57**	**3.4**

Conversion to At-Satellite Brightness Temperature

TIRS band data can be converted from spectral radiance to brightness temperature using the thermal constants provided in the metadata file and the following equation:

$$T_{sen} = \frac{k_2}{\ln(\frac{k_1}{L_\lambda}+1)}$$

where:

T_{sen} = At-satellite brightness temperature (K)
L_λ = TOA spectral radiance (Watts/(m^2 * srad * µm))
K_1 = Band-specific thermal conversion constant from the metadata (K1_CONSTANT_BAND_x, where x is the thermal band number)
K_2 = Band-specific thermal conversion constant from the metadata (K2_CONSTANT_BAND_x, where x is the thermal band number)

- Use the **Create Band from Math Expressions** to calculate LST (you will need a four step procedure)
  1. Create the brightness temperature (name it T_{sen}) for band 10 (TIRS_1)

  [Use the expression: 1321.0789/(log((774.8853/'thermal_infrared_(tirs)_1')+1)). Find the log in the "Functions"] (Figure 13).

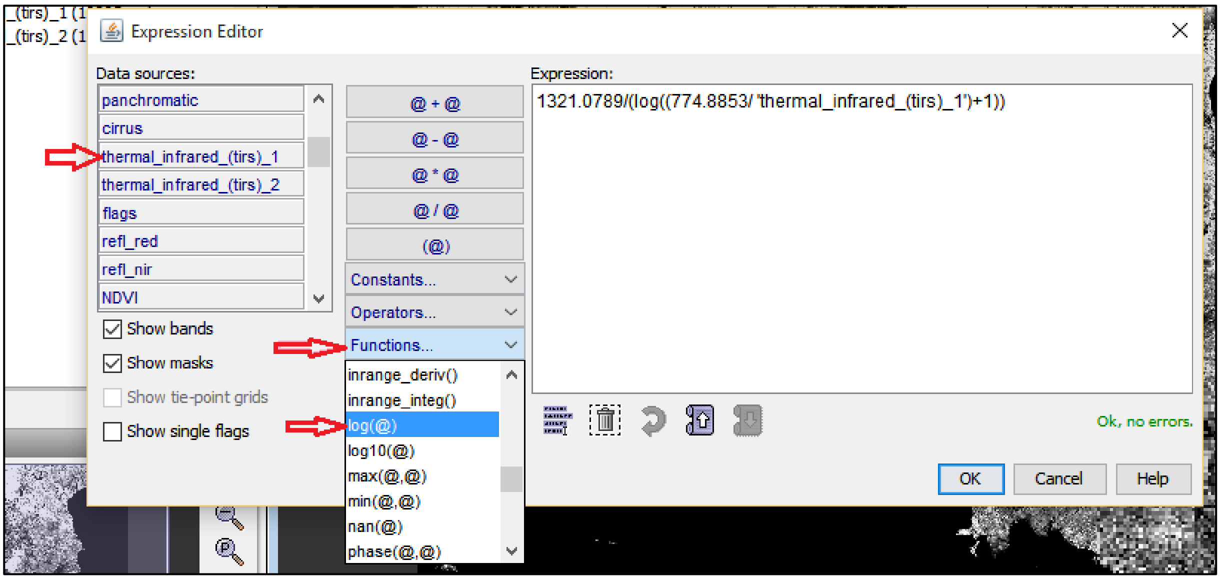

Figure 13

2. Create γ (name it gamma). (Remember that $\gamma \approx \frac{T_{sen}^2}{b_\gamma}$)

[use the following expression: (T_{sen}*T_{sen})/(1324*'thermal_infrared_(tirs)_1')]

3. Create δ (name it delta). (Remember that $\delta \approx T_{sen} - \frac{T_{sen}^2}{b_\gamma}$)

[use the following expression: T_{sen}-((T_{sen}*T_{sen})/1324)]

4. Create the land surface temperature image (name it LST). (Remember that LST= $\gamma\cdot[1/LSE\cdot(\psi_1\cdot L_{sen} + \psi_2) + \psi_3] + \delta$)

[use the following expression:

gamma*((1/LSE)*(1.3513*'thermal_infrared_(tirs)_1'-6.53)+3.57)+delta]

Finally use the colour manipulation tool to colour your LST image (Figure 14). You can zoom in your area of interest (Athens or Budapest) (Figure 15).

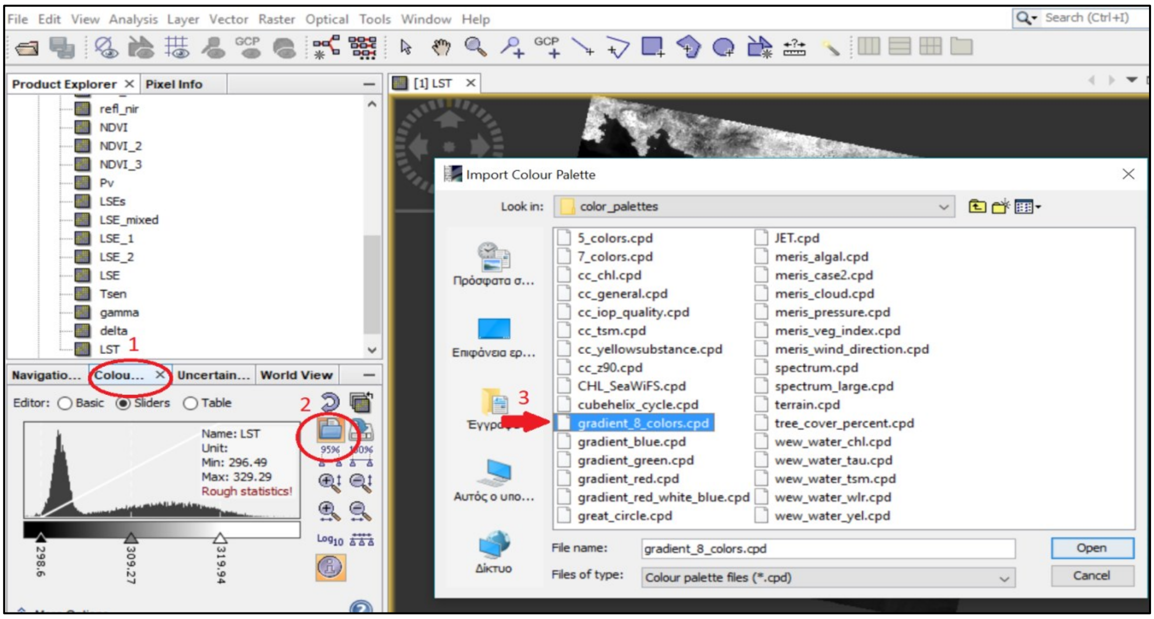

Figure 14

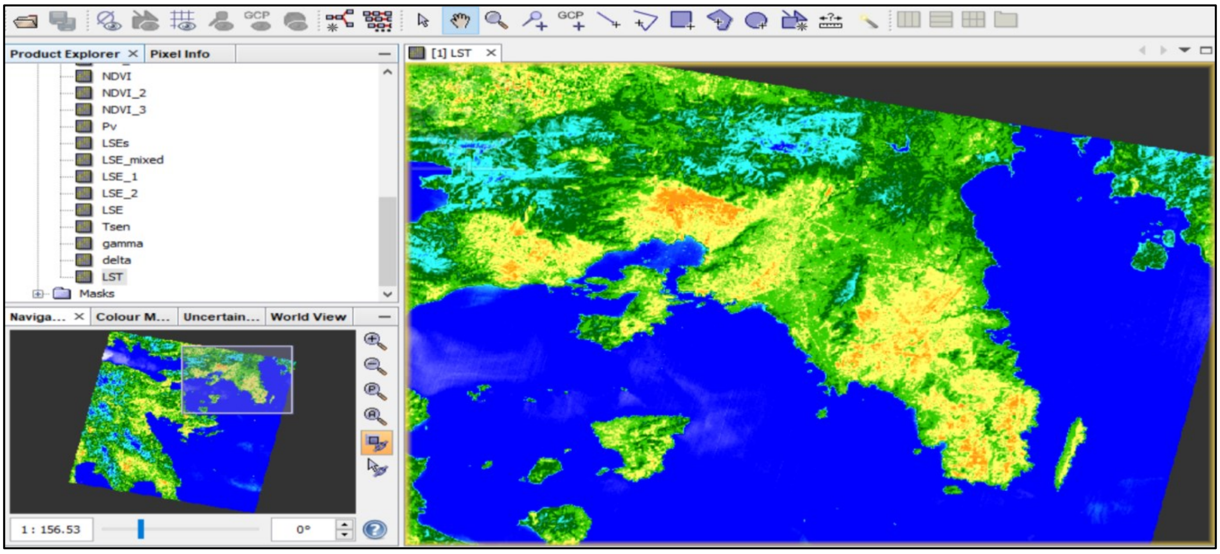

Figure 15

B. Monitoring the urban heat island of Athens and Budapest with the use of Sentinel 3 data

The Sentinel-3 (S3) mission of ESA is one of the elements of the GMES (Global Monitoring for Environment and Security) program, which responds to the requirements for operational and near-real-time monitoring of ocean, land and ice surfaces over a period of 20 years. The Sentinel-3 mission is designed as a constellation of two identical polar orbiting satellites, separated by 180º, for the provision of long-term operational marine and land monitoring services. The operational character of this mission implies a high level of availability of the data products and fast delivery time, which have been important design drivers for the mission. The Sentinel-3A spacecraft was launched on February 16, 2016.

The satellite, designed for a minimum lifetime of 7 years, is carrying a payload which includes:

- The Sea and Land Surface Temperature Radiometer (**SLSTR**), with strong heritage from AATSR instrument on Envisat, will monitor the impact of climate changes on the temperature of our oceans as well as of the emerged land, and improve meteorological forecasts by fostering a better understanding of the relationship between oceans and the atmosphere.

SLSTR is a dual scan temperature radiometer, which has been selected for the low Earth orbit (800 - 830 km altitude) ESA Sentinel-3 operational mission as a part of the Copernicus (Global Monitoring for Environment and Security) programme. The principal objective of SLSTR products is to provide global and regional Sea and Land Surface Temperature (SST, LST) to a very high level of accuracy (better than 0.3 K for SST) for both climatological and meteorological applications.To achieve near-global coverage and meet all scientific requirements, Sentinel-3 will be placed in a high-inclination, sun-synchronous polar orbit. Near-realtime data processing and delivery will allow operational services to continuously profit from the mission.

In this exercise we will use the SLSTR Level-2 LST product which provides land surface parameters generated on the wide 1 km measurement grid. It contains measurement files with Land Surface Temperature (LST) values with associated parameters (LST parameters are computed and provided for each pixel included in the 1 km measurement grid. It also contains data of Normalized Difference Vegetation Index (NDVI), GlobCover surface classification code (noted biome), fractional vegetation cover and total column water vapour.

Exercise steps

1) Open the SNAP Toolbox and import the Sentinel 3 data

- Select **File→ Import→ Optical sensors→ Sentinel-3→ Sentinel-3** (Figure 16)

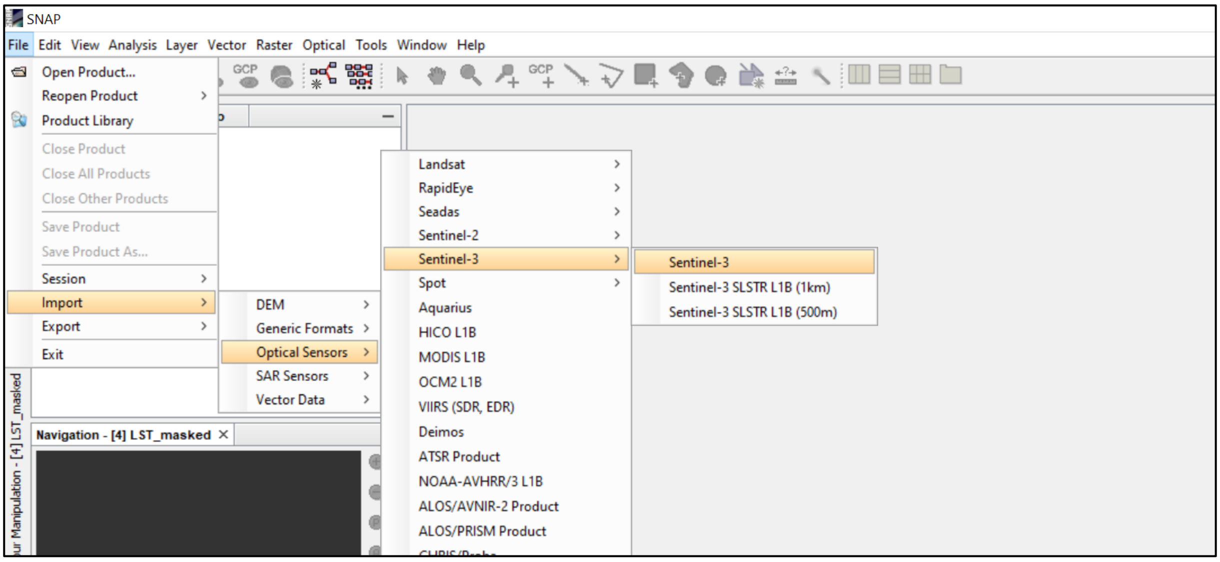

Figure 16

- Select the first file in the Sentinel 3 folder of Athens (Figure 17), open the **xfdumanifest.xml** file that is inside it and click on "Import Product" in the dialog box (Figure 18). This image was acquired on 12 July 2017 at 08:42 UTC as it can be extracted from the filename "S3A_SL_2_LST___***20170712T084222***…" so it is suitable for the monitoring of the daytime urban heat island.

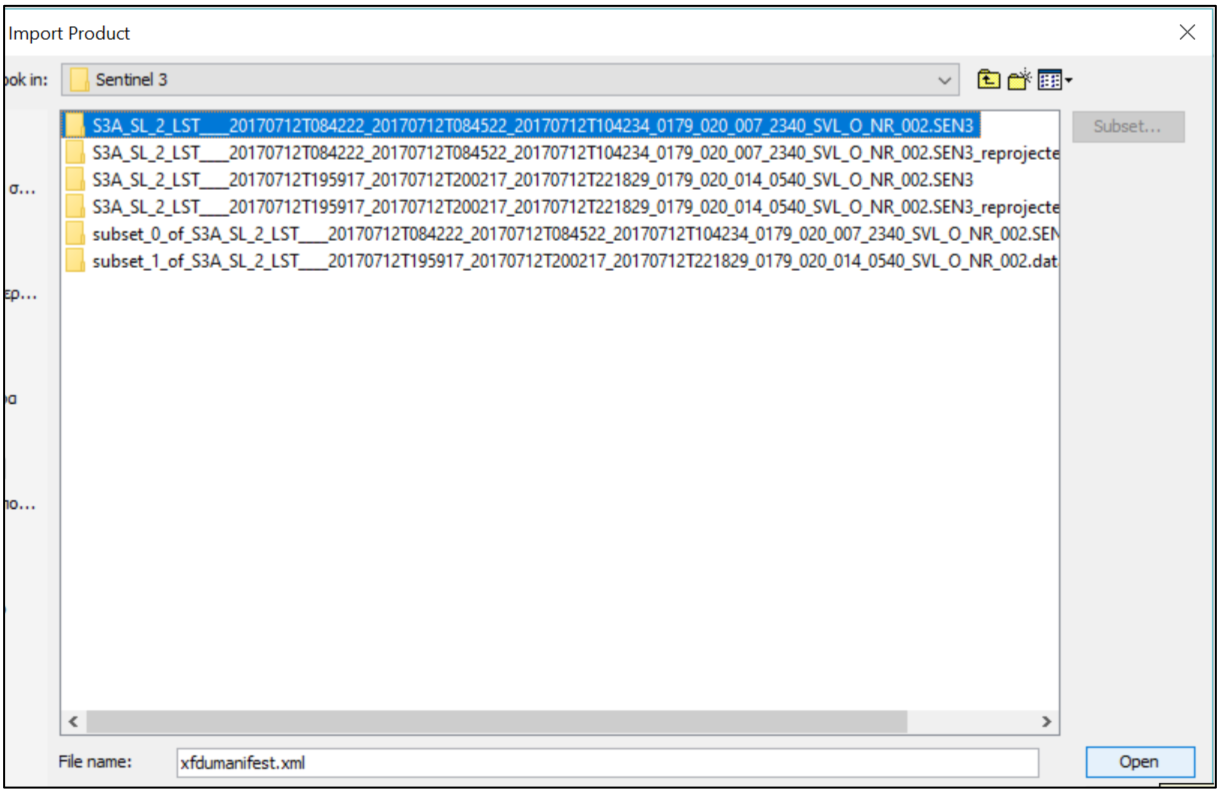

Figure 17

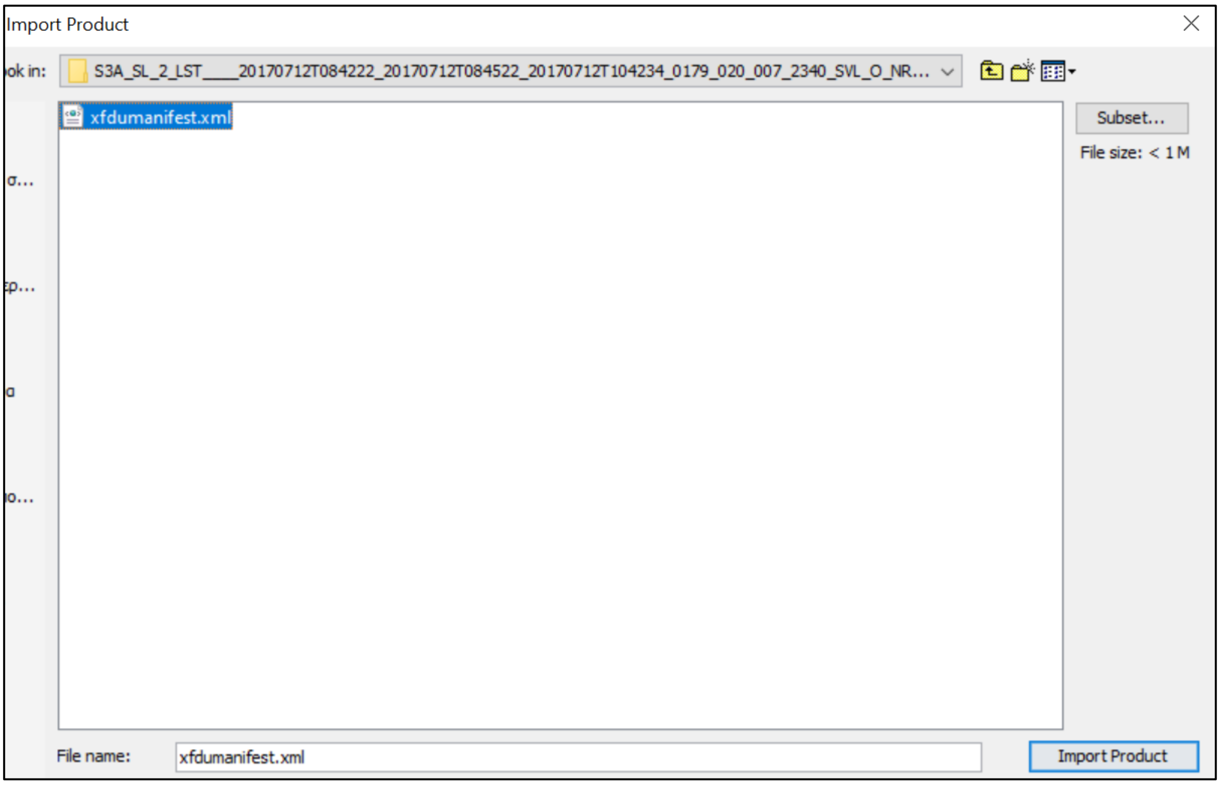

Figure 18

- Now you have imported the Sentinel 3 data to SNAP toolbox. In the "Product Explorer" window you can see the metadata files and the bands. Double click on the LST band to open the image data. In the "Pixel info" window you can see that the LST is given in Kelvin (Figure 19). Notice the wide spatial coverage of the Sentinel 3 data compared to the Landsat 8 data.

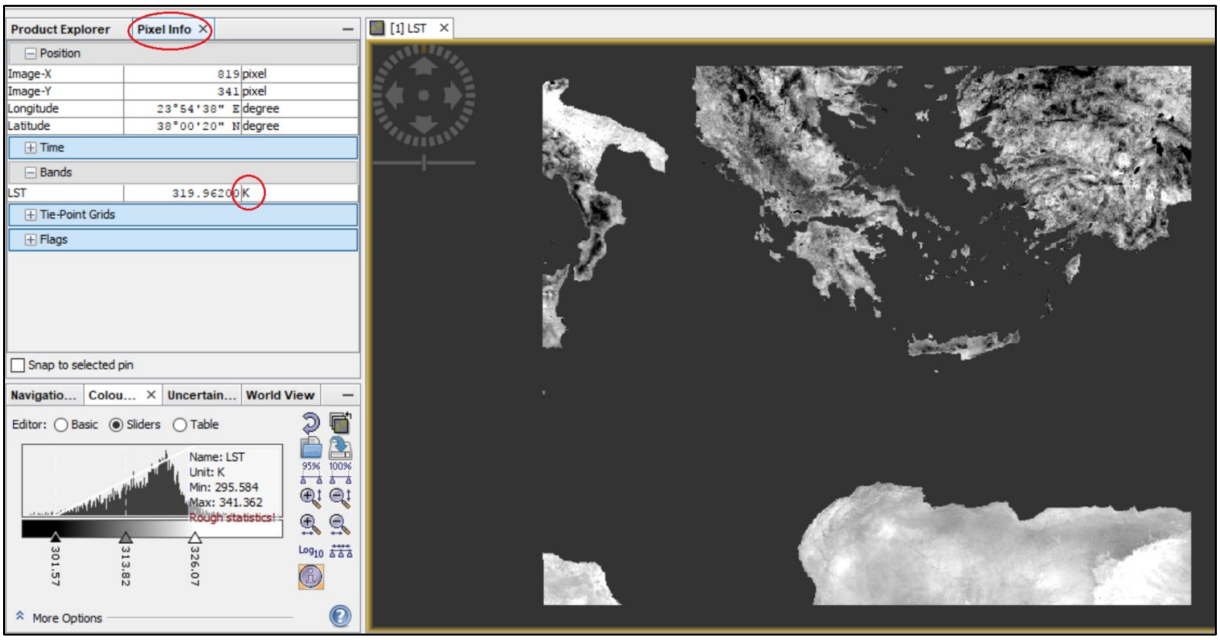

Figure 19

2) Next we will reproject the Sentinel 3 data to the coordinates reference system of Landsat 8 (EPSG:32634)

- Select **Raster→ Geometric Operations→ Reprojection** (Figure 20).

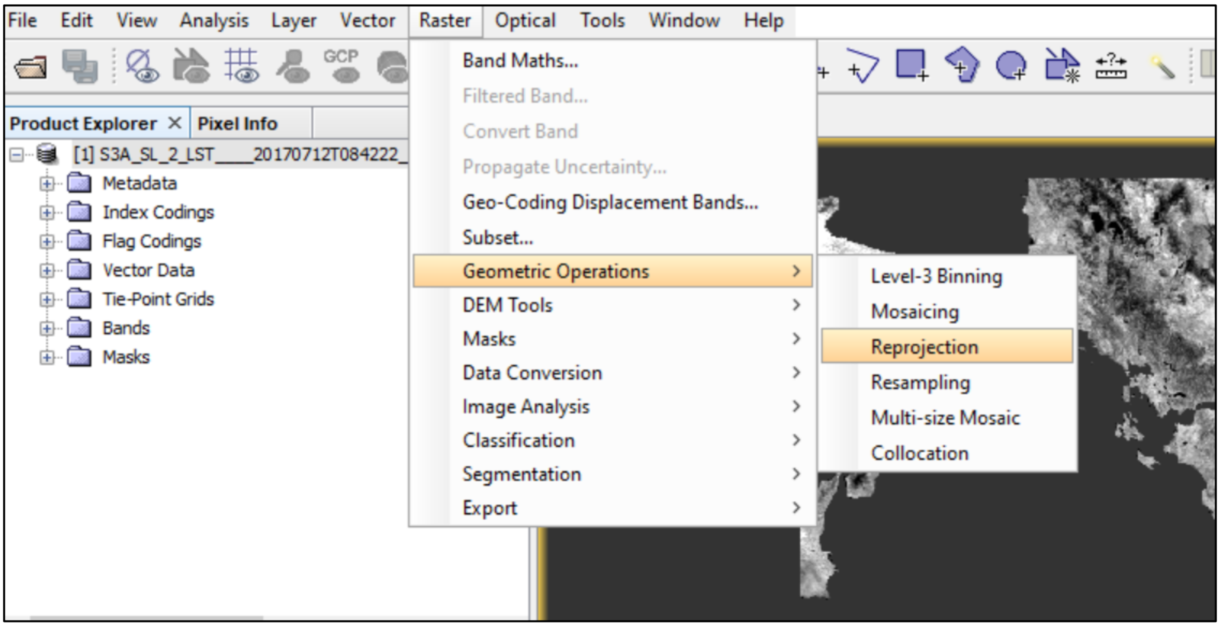

Figure 20

- In the Reprojection window select the **Reprojection parameters** tab and select the "**Predefined CRS**" option (Figure 21). "**Select**" the EPSG:32634 by typing the number 32634 in the Filter section. In the I/O Parameters tab select a folder to save the reprojected data.

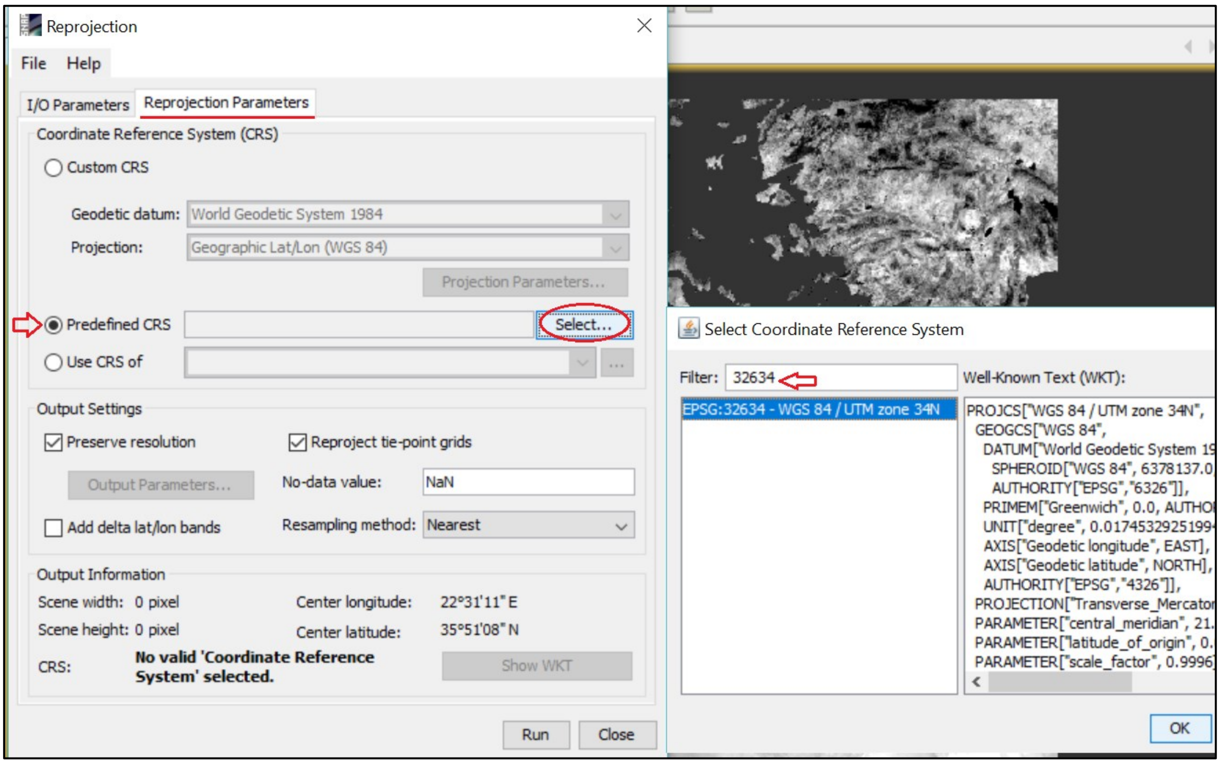

Figure 21

3) Your reprojected data will appear in the "**Product Explorer**" window. Open the LST band of the new image [indexed as (2)] and zoom in the wider Athens area. Right-click in the image and select "**Spatial Subset from View…**" (Figure 22).

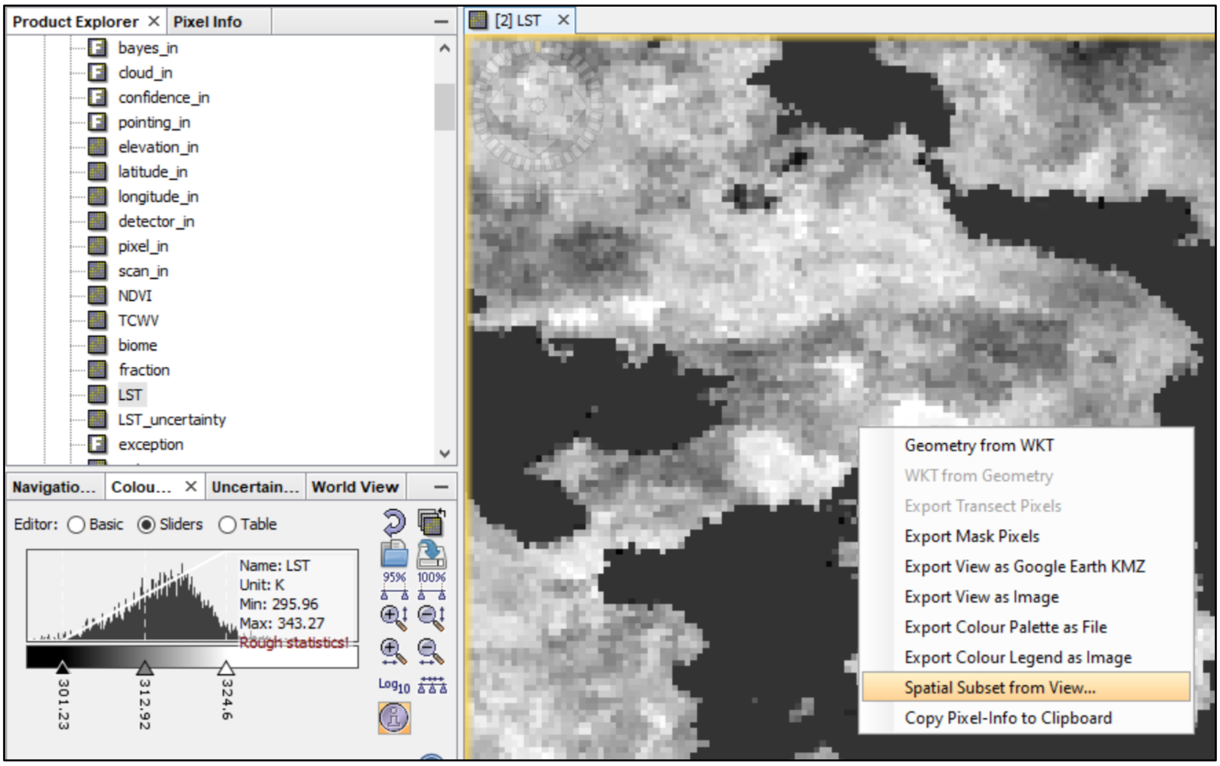

Figure 22

- In the "**Specify Product Subset**" window select the "**Band Subset**" tab and select only the LST, NDVI, biome and fraction bands (Figure 23). Press "**OK**" and then "**NO**" in the message that pops up about the flags.

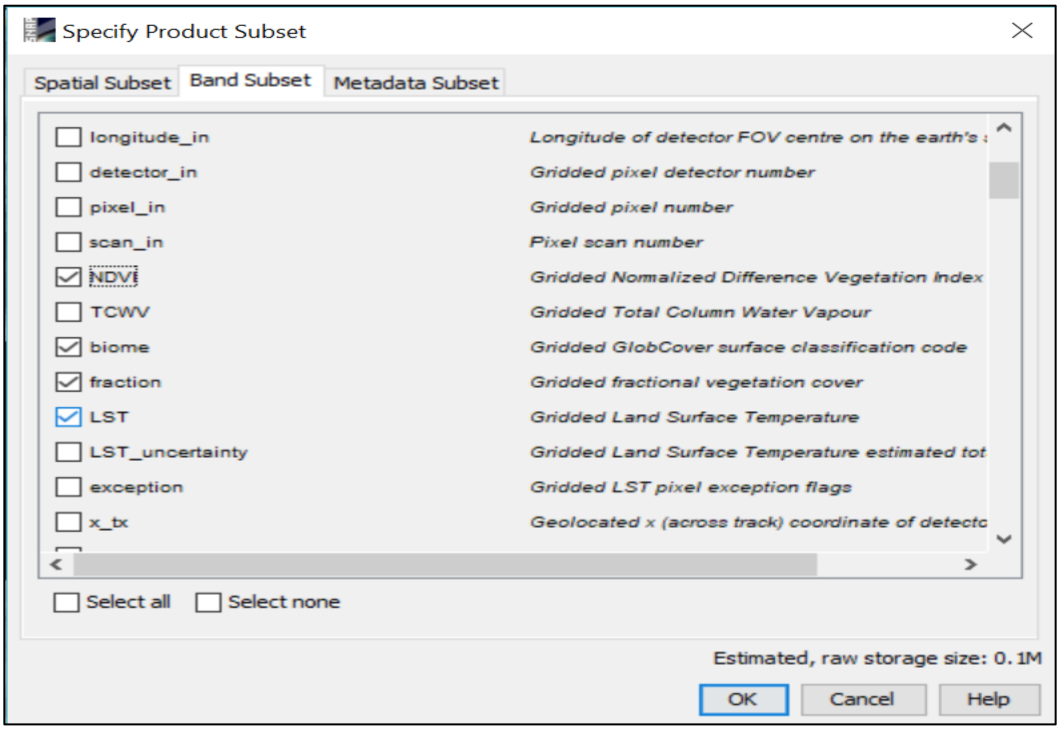

Figure 23

- Choose the newly estimated image (named as subset) and use the colour manipulation tool to colour your subset image (Figure 24).

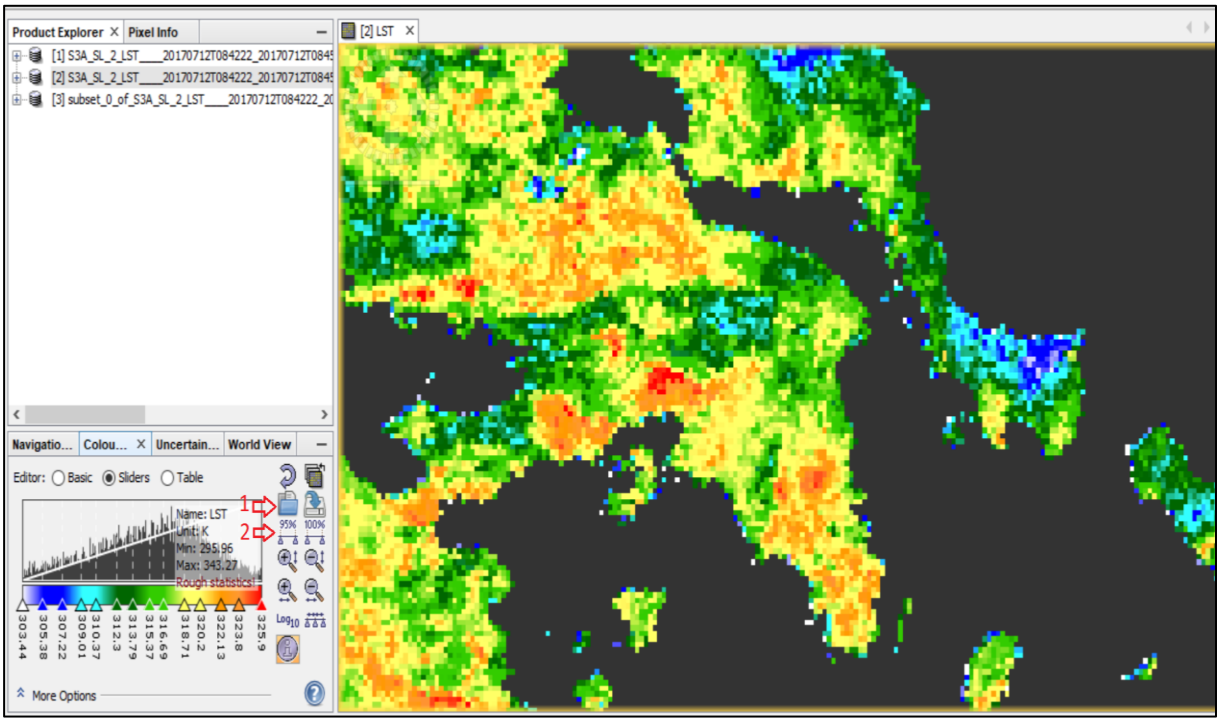

Figure 24

4) In order to monitor the nighttime urban heat island we should repeat the same steps for the nighttime image. To save computational time we have already processed the nighttime image. You can open it by selecting **File→ Open Product** and opening the file “**subset_Athens_night.dim**” that you will find in the Athens→ Sentinel 3 folder of your data (Figure 25).

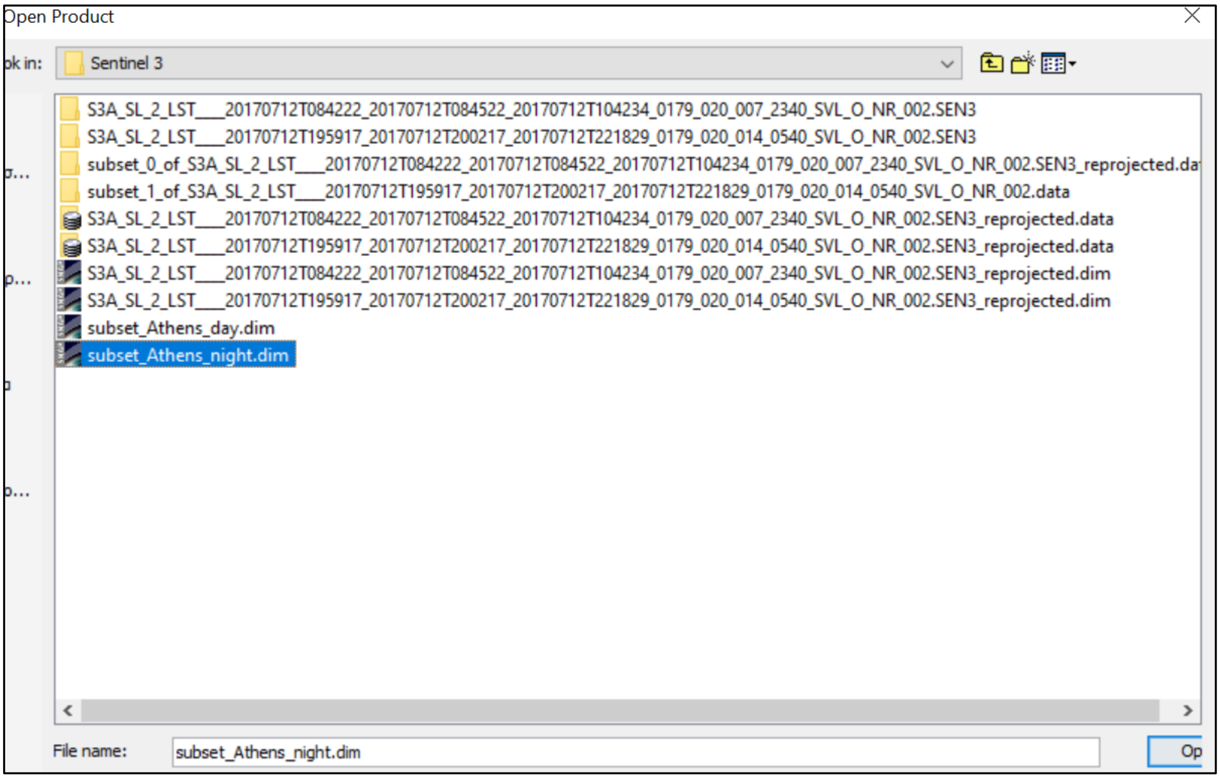

Figure 25

5) Colour your nighttime image and compare the LST distribution of the daytime and nighttime data.

In addition you can find a subset daytime image of the LST of Budapest in the Budapest→ Sentinel 3 folder (Unfortunately no nighttime cloud free image of Budapest was available during the development of this tutorial).

References

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