Monitoring Urban Heat Island through Google Earth Engine: potentialities and difficulties in the case of Phoenix, Arizona

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Abstract: Climate change and sustainable development are strongly interconnected both in the realm of research and in the realm of politics. The sustainable Development Goal 13, one of the 17 proposed objectives (SDGs), reads: "Take urgent action to combat climate change and its impacts". To achieve this, a new mentality is needed in order to implement new policies and to find innovative solutions. The purpose of this thesis is primarily to develop a new methodology that allows the phenomenon of the Urban Heat Island (UHI) to be monitored in an increasingly precise, fast and efficient manner. In particular, with the aim of exploiting the immense potential of the latest generations of Earth Observation (EO) satellites, the global-scale analysis capability of Google Earth Engine (GEE) is used to investigate the temporal variations of the UHI in the metropolitan city of Phoenix (Arizona). The results show that the proposed method allows the prediction of UHI trends, thus giving valuable indications to address the more and more sustainable urban planning of our cities.

1. INTRODUCTION

Google Earth Engine (GEE) is the computing platform recently released by Google "for petabyte-scale scientific analysis and visualization of geospatial datasets". Using a dedicated High Performance Computing (HPC) infrastructure, it enables researchers to easily and quickly access more than thirty years of free and public data archives, including historical imagery and scientific datasets, for global and large scale remote sensing applications. In this way, many of the limitations related to data downloading, storage and processing are effortlessly overcome.

In particular the aim of this thesis is to show the present potential of (GEE) to process the huge and continuously increasing free EO Big Data (i.e. Landsat and Sentinels imagery) for long-term spatio-temporal monitoring Urban Heat Island (UHI) and its connection with the Land Cover (LC) changes.

Specifically, the term UHI refers to the mesoscale phenomenon associated with higher atmospheric and surface temperatures occurring in urban environments than in the surrounding rural areas due to urbanization. It is characterized by a large expanse of non-evaporating impervious materials covering most of urban areas with a consequent increase in sensible heat flux at the expense of latent heat flux. Therefore, the UHI and its spatio-temporal evolution are connected to the LC changes, mainly to the transformation from non-urban to urban LC. Traditionally, the UHI is investigated using ground-based in-situ measurements of air temperature acquired by automatic weather stations. Air temperature measurements allow indeed to characterize the fine spatial and temporal variations of the UHI, and they are suitable for studying impacts of local indicators of urbanization (e.g., sky view factor, floor area ratio) and climate factors (e.g., wind, cloud) contributing to the phenomenon.

Nonetheless, the urban meteorological networks are not always as complete as could be desired, and frequently their stations are not uniformly distributed within the territory of the investigated cities. Consequently, large zones may remain without coverage and it is not possible to analyze the different spatial pattern.

On the other hand, remote sensors on board of the satellites are able to acquire thermal infrared data from which is possible to retrieve the urban Land Surface Temperature (LST), allowing thus the study of the UHI. The major advantage of the UHI is that it can be calculated easily for many cities across large spatial domains. This allows to investigate the role of urbanization in influencing the UHI over large regions.

The focus is the Metropolitan Areas of Phoenix, which experienced a significant urban expansion in the last decades, indeed, from 1983 to 2010 this city underwent a significant expansion, changing from a mostly agricultural region to a metropolis predominantly characterized by residential suburbs.

2. DATA AND METHODS

The developed methodology implements a large-scale correlation analysis between the Land Surface Temperature (LST) and LC alterations through the joint use of GEE and Climate Engine (CE), a free web application powered by GEE, enabling users to process, visualize, and download various global and regional climate and remote sensing datasets and products in real-time.

Specifically:

1. the annual median of the LST was computed through CE from the Landsat Top of Atmosphere Reflectance Data for every year of the temporal period comprised between the 1992 and the 2011 over the Region Of Interest (ROI) corresponding to the considered

MA. The ROI was selected in order to capture surface variability and to consider surface portions remained unchanged and purely rural. Preliminarily, it was verified that each year had a good seasonal distribution of images, in order to avoid considering more summer or winter images that could compromise a good estimate.

2. the LC data were directly retrieved through GEE from the USGS National Land Cover Database (NLCD, Figure 3) on the same ROI for the 1992 and 2011 years, respectively.

2.1 Land Surface Temperature

The CE web application was used to compute the annual median of the LST over the Landsat 4/5/7 Top of Atmosphere Reflectance Data, for every year of the two decades comprised between 1992 and 2011 in the ROI. The use of a robust estimator such as the annual median guarantees a good reliability of the methodology, especially at the beginning of the analysis period, where the number of the available images is lower and sometimes slight inhomogeneities are present.

In this way, 20 thermal images (each one relative to a single year) were obtained in which the value stored in every pixel is the median of the LST computed over all

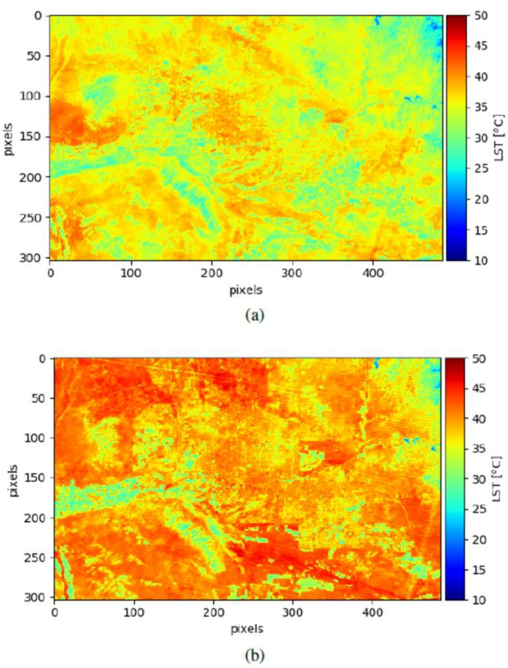


Figure 1: LST 1992 (a) and 2011 (b) obtained through CE for the considered ROI.

the Landsat images available in CE for the considered year. Figure 1 reports two examples of such images, respectively for the years 1992 and 2011, where it is possible to notice a general increase of the LST.

The analysis showed that a linear model can be considered as a reasonable approximation of the phenomenon. Thus, for every pixel of the ROI, the parameters of a simple linear model:

$$T = T_o + r\,(t - t_o)$$

describing the LST trend as a function of time were robustly estimated; here, T is the LST, T_0 is the estimated LST referring to t_0 (the analysis starting year, here 1992), t is the current time and r is the rate of the temperature variation per year.

Thus, the two maps illustrated in Figure 2 were computed: they show the same increasing LST trend (m > 0) observed in Figure 1, characterized by variable rates within the ROI.

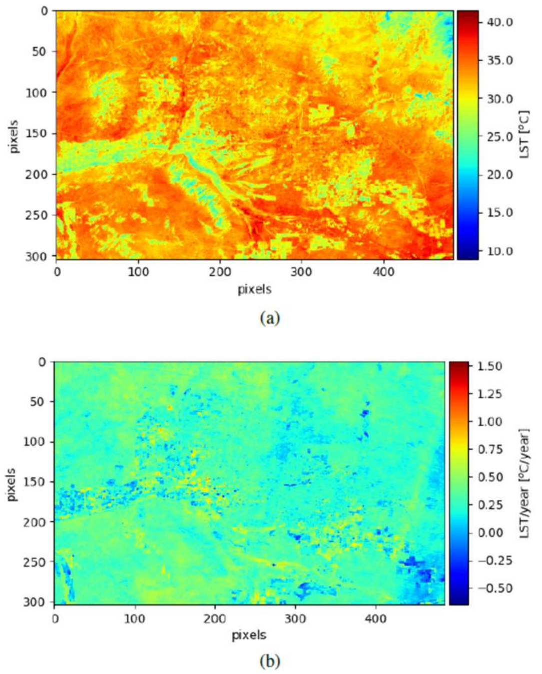


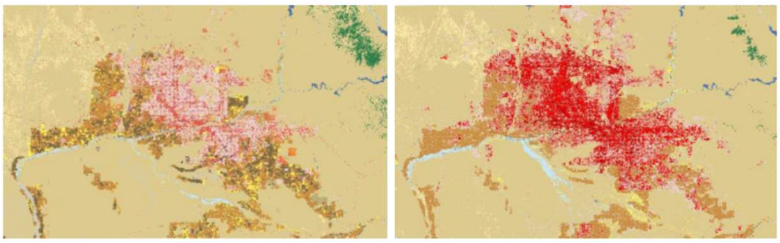
Figure 2: Map of the constant (a) and slope (b) parameters of the LST linear model Eq. 1 on the investigated ROI.

2.2 National Land Cover Database

The USGS National Land Cover Database (NLCD) was used to assess the LC changes that occurred in the city of Phoenix during the twenty years under consideration. The NLCD is a 30 m Landsat-based land cover database spanning four periods (1992, 2001, 2006 and 2011). It was directly retrieved from GEE on the ROI for the year 1992 and 2011.

Specifically, the database provides an LC classification for functional classes whose identification codes suffered some modifications during the considered interval 1992-2011: indeed, the NLCD classification scheme used for the NLCD1992 product differs slightly from that adopted in the more recent products (i.e. NLCD2001, NLCD2006, NLCD2011). In order to overcome this problem and to compare LC homogeneous data, the various LC classes were grouped into main four classes related to urbanized, cultivated and forest/shrubland areas as follows:

1. *Low Intensity Residential*: includes areas characterized by a mixture of constructed materials (30%-80%) and vegetation (70%-20%). These areas most commonly include single family housing units. Population density is lower than in high intensity residential areas.
2. *High Intensity Residential*: includes highly developed areas where people reside in high numbers such as apartment complexes and row houses. Vegetation accounts for less than 20% of the cover; the remaining part corresponds to constructed materials.
3. *Shrubland*: areas dominated by shrubs; shrub canopy accounts for 25%-100% of the cover. Considering that the city of Phoenix is located in the north-eastern reaches of the Sonoran Desert, this class corresponds to the (scarce) desert vegetation, i.e. to the desert itself.
4. *Row Crops*: rural areas used for the production of crops, such as corn, soybeans, vegetables, tobacco, and cotton.



(a) 1992 (b) 2011

Figure 3: NLCD for the Phoenix MA.

(a) 1992 (b) 2011

Figure 4: NLCD legends.

1992		2011	
LC classes	LC code	LC classes	LC code
Low Intensity Residential	21	*Developed, Low Intensity*	22
High Intensity Residential	22	*Developed, High Intensity*	24
–	–	*Medium Intensity Residential*	23
Commercial Industrial/Transportation	23	–	–
Shrubland	51	*Shrub/Scrub*	52
Row Crops	82	*Cultivated Crops*	82

Table 1: NLCD codes variation over the years 1992-2011.

Moreover, after grouping in the chosen three main classes, an under sampling with the same factor 10 as before was performed on the LC database; in this way, the spatial resolution of the derived LC database for the investigated MA is equal (300 meters GSD) to the one of the derived parameter maps, allowing a one-to-one pixel correspondence. This is a simplification, but it is convenient to highlight the main influences of the long-term relevant LC changes (from rural - cultivated and forest/shrubland - to urban areas and viceversa) on the variations experienced by the LST over the considered period.

2.3 Correlation between Land Surface Temperature data and Land Use data

A spatial analysis was performed to find a possible correlation between the observed LST trends and the corresponding changes in the LC data. Operatively, based on the adopted linear temperature growth model (Equation 1), a (4*4) matrix (Rate Matrix) was computed for the MA investigated for the rate (r) parameter. In particular, each cell (i,j) of this matrix (Figure 5):

- aggregates all the ROI pixels characterized by the LC class i in the initial year (1992) and the LC class j in the final year (2011);
- stores on three different layers the hereafter described statistical parameters (mean, median, numerosity, Permanence-Variation Index), computed considering the values of r of all the ROI pixels which underwent the LC change from class i to class j.

A schematic representation of the obtained Rate Matrix is shown in Figure 5.

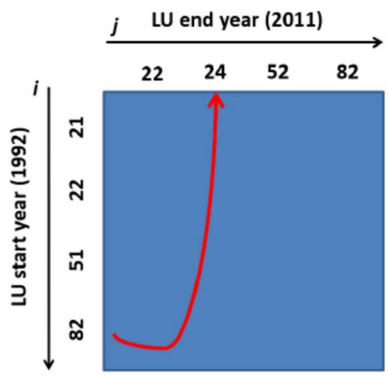


Figure 5: Representation of the LC changes within the Rate Matrix: the row index (i) represents the initial LC class, the column index (j) represents the final LC class. For example, the LC transition from the class Row Crops to the class High Intensity Residential (from i = 51 to j = 24) is indicated with the red arrow.

2.3.1. Numerosity

This layer quantifies the number of ROI pixels effectively involved in the change from the LC class i to the LC class j. Therefore, the values on the main diagonal indicate the number of stable pixels, which did not change their original LC and which constitutes, as expected, the largest portion. Then, there are the pixels that from purely rural classes (Cultivated or Forest/Shrubland) turned into urban ones (lower triangle) or viceversa, (upper triangle); finally, there are also pixels changing within rural classes (from Cultivated to Forest/Shrubland or viceversa). Recalling that the pixels have a 300 m GSD, it is possible to infer the surface of the ROI that underwent a specific LC change from their numerosity.

2.3.2. Mean, Median

In these layers, the mean and the median of the parameters of the linear model describing the LST trend for the considered LC change from class i to class j are stored. The values obtained are very similar for both the statistical parameters, pointing out the substantial absence of outliers. Therefore, for sake of brevity, only the mean value was considered in the analysis.

2.3.3 Permanence/Variation Index

The overall evaluation of the LC changes which occurred in the investigated ROIs has been represented through the here introduced temporal Permanence/Variation Index, defined as follows:

$$I_v = \frac{n_{ij}}{\sum_j n_{ij}}$$

where n_{ij} is the number of the ROI pixels involved in the change from the LC class i to the LC class j.

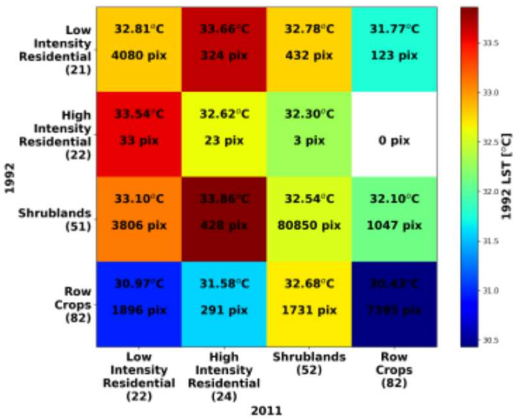
Therefore, I_v represents an index of permanence for the elements belonging to the main diagonal (here usually the highest values are observed), whereas it represents an index of variation for the elements in the lower and upper triangles, defining the frequency of occurrence of the changes experienced by each individual LC.

3. RESULTS

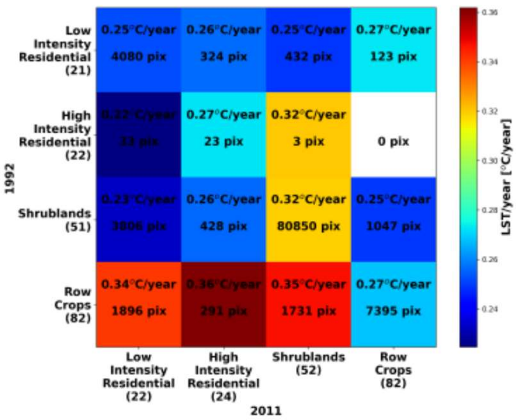
For the city of Phoenix, the developed methodology was applied to a ROI of about 13340 km^2, corresponding to the MA itself plus its rural and desert surroundings. To speed up the computation, the results were generated considering a spatial resolution of 300 m, ten times the original Landsat resolution (30 m).

Figure 7 (a) (b) illustrates separately the spatial distribution of the four considered LC classes, in 1992 and 2011 respectively: it is evident that the (desert) Shrubland class is predominant, because of the desert nature of Phoenix. Conversely, the High Intensity Residential class included a limited number of pixels in 1992 which however increased in 2011, as also those belonging to the Low Intensity Residential class. Such urban expansion was prevalently obtained at expenses of the rural areas which decreased significantly in the investigated temporal period.

The obtained results are also shown in Figure 6, where the Slope Matrix and the Constant Matrix are reported.



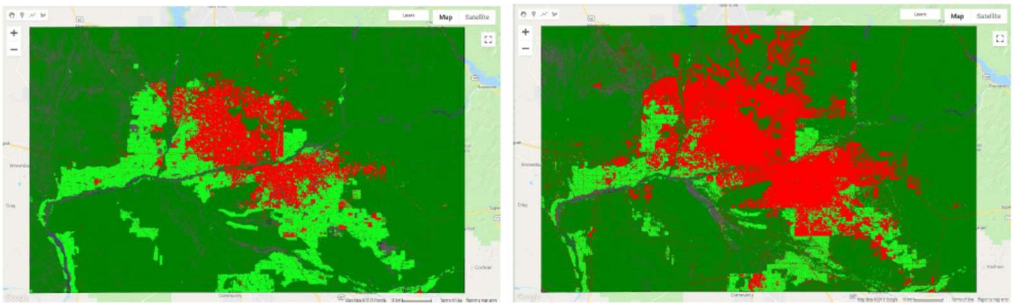
(a) Constant matrix



(b) Slope matrix

Figure 6: Matrices.

On their main diagonals, there are the ROI pixels whose original LC remained unaltered: they form, as expected, the more numerous group. Then there are the pixels which underwent the LC transitions from the classes Row Crops or Shrublands to the classes Low Intensity Residential or High Intensity Residential, changing their nature from purely rural to urban. The abandonment of the rural areas is instead reflected in the LC transformation from the class Row Crops to the class (desert) Shrublands, which involved a consistent number of pixels. Lastly, there are the “urban-rural” transitions, i.e. from Low Intensity Residential or High Intensity Residential to Shrublands or Row Crops, but they are not statistically significant since they involve a very limited number of pixels.



(a) 1992 (b) 2011

Figure 7: Phoenix MA_LC situation in 1992 (a) and in 2011 (b). In red the Urbanized class, in light green the Cultivated class, in dark green the Forest and Shrubland classes.

The Rate Matrix was detrended for the general LST increase, in order to highlight the net effects of the LC changes and the specific role of the urbanization. In detail, the LST trend was separately removed from each row of the Rate Matrix, by subtracting the values pertaining to the main diagonal (i.e. the cell representing the permanence in the same LC class during the investigated period) from those related to the other two cells (which represent the changes among the LC classes). In this way, the so-called Detrended Rate Matrix was computed, in which only the LST increase effectively due to the LC variation is considered and, obviously, the values on the main diagonal are zero.

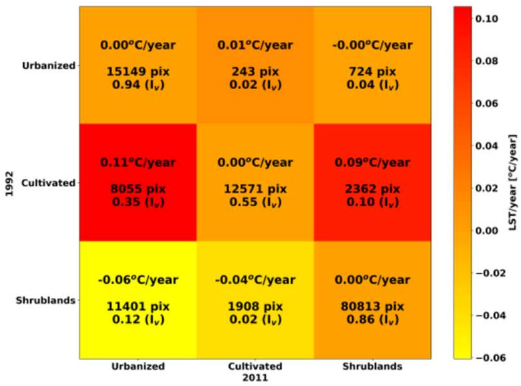


Figure 8: Phoenix MA: Detrended Rate Matrix

The developed methodology is able to detect effectively the LST trends connected to LC changes. Indeed, the Cultivated-Urbanized change results characterized by the highest increasing LST rate (0.11°C/year).
On the contrary, a negative LST increasing rate (-0.06°C/year) can be observed in the LC change from Shrublands (desert) to Cultivated, while a positive increasing rate (0.09°C/year) can be noticed in the reverse change. The first situation corresponds to the ROI pixels that become cultivated and thus irrigated, whereas the latter is related to the abandonment of the rural areas, which thus were no longer irrigated.

4. CONCLUSIONS

In this work, an intuitive methodology was developed to investigate the temporal variations of the UHI effects as a whole, based on the large-scale analysis capabilities of GEE.
A general procedure was defined and implemented, thanks to the joint use of GEE and CE, and the indicator Detrended Rate Matrix was introduced to globally represent the net effect of LC changes on UHI.
The application of the Detrended Rate Matrix evidenced a strong correlation between the highest increasing LST rates and the transformations from rural to urbanized LC was found.
Specifically, the promising results regarding the Phoenix MA were presented: they clearly show how the urbanization heavily influences the UHI magnitude with significant increases in LST. The proposed methodology is therefore able to efficiently monitor the UHI phenomenon and in an increasingly precise and fast way.
Nevertheless, it is however necessary to validate such methodology on other MAs, characterized by different weather conditions and not located in desert regions. Moreover, it could be also worth to analyze the LC data in an aggregate way, in order to avoid losing those LC classes not completely equivalent in the two considered classification schemes.
The present feasibility of the proposed procedure and the encouraging obtained results, although preliminary and requiring further investigations, pave the way for a possible global service on UHI monitoring, able to provide valuable indications to address an increasingly sustainable urban planning of our cities.

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