Calculation of surface urban heat index from LANDSAT-8 TIRS data and its relation with land cover

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Abstract—Urban localities are mainly covered by concrete and asphalt paving material, which are impermeable surfaces with higher heat absorption capacity and a lower albedo, thus absorbing more radiation compared to the surrounding countryside. The urban surface heat island effect is described as a higher surface temperature in cities compared to a cooler temperature in surrounding areas. Canopy layer urban heat island (HI) are typically detected by in situ sensors at standard (screen-level) meteorological height. On the other hand, thermal remote sensors observe the surface urban heat island index (SUHI). The aim of this work is to calculate the spatial distribution of the SUHI index in Córdoba city and its metropolitan area, and to analyse its relationship with different land covers using satellite information.

Córdoba city, located in the central region of Argentina, is the second most populated city in the country. A LANDSAT-8 image of the study area was used to calculate urban heat index (UHI), SUHI, and UHII. Urban and Non-urban region were defined and compared. It was observed that the same type of land use has significant different temperature mean value depending on whether it is located on an urban island or in a rural or open environment.

Index Terms—LANDSAT 8, surface temperature, SUHI, land cover, heat island, metropolitan area

I. INTRODUCTION

In a global changing world, which is under continuous natural threats, cities should have sustainable development as their main objective [1], [2]. However, as the value of land increases, green areas and public spaces give way to residential housing and businesses. The strong influence of these changes can be observed in the energy balance of the existing environment resulting in the urban heat island effect.

The urban surface heat island effect is described as a higher surface temperature in cities compared to a cooler temperature in surrounding areas [3], [4]. For this reason, it is of great important to preserve public green spaces, as they have the function of cooling their surroundings. In most urban localities, roads, buildings and other structures are covered by concrete and asphalt paving material. These surfaces are impermeable with higher heat absorption capacity and they have a lower albedo, thus absorbing more radiation compared to the surrounding countryside [5]. According to global warming forecasts, heat waves are likely to increase in frequency and intensity in the future [6]. In addition, heat waves have the potential to negatively affect the health of urban residents [7].

The type of land cover is a determining factor in the thermal behaviour of the earth’s surface, and much research has been carried out indicating the impact of pavement on the increase in surface temperature [8]. Atmospheric heat islands may be defined for the urban canopy layer (UCL), as the layer of the urban atmosphere extending upwards from the surface to approximately mean building height, and the urban boundary layer, which is the layer above the UCL that is influenced by the underlying urban surface [9]. Canopy layer urban heat island (HI) are typically detected by in situ sensors at standard (screen-level) meteorological height. On
the other hand, thermal remote sensors observe the surface urban heat island index (SUHI), or, more specifically they ‘see’ the spatial patterns of upwelling thermal radiance received by the remote sensor and its definition take into account the surroundings [9], [10]. There are several ways to take into account a reference temperature far from urban area to calculate SUHI index. Mostly, these reference zones are surrounding area or a dense forest patch [8], [11]. However, for the best of our knowledge, there are not studies focused on quantify differences in temperature for the same land cover, but located inside and outside the cities. The aim of this work is to calculate the spatial distribution of the SUHI index in Córdoba city, Argentina, and in its metropolitan area, and to analyse its relationship with different land covers using satellite information.

II. MATERIALS AND METHODS

A. Study Area

The study area is the city of Córdoba, including the northwest metropolitan region, and its surroundings. Córdoba is located in central Argentina and it is the second most populated city in the country, after Buenos Aires, and the largest in extension. At the moment of the official census query, 2010 year, it had a population of 1329604 people and more than 400000 in its northwest metropolitan region. Figure Fig.1 corresponds to a LANDSAT 8-OLI RGB image from the date 28/02/2019 which was acquired over the study area. Pink shadow correspond to urban zones, while blue shadows correspond to its surroundings which will be considered in this study. It is delimited to the north by the parallel 31°18’30”S, to the east by the meridian 64°03’27”W, to the south by the parallel 31°31’30”S and to the west by the meridian 64°18’35”W, with a height above sea level between 352 and 544 meters, at East and southwest corner of the city respectively. The climate of this region is temperate subtropical humid with dry winter and high thermal amplitude.

B. Satellite data

A LANDSAT-8, Level 2 Collection 2 (L2C2) image, scene 229/82 acquired on February 28th of 2019, downloaded from the USGS US Geological Survey server (https://earthexplorer.usgs.gov/) was used. The L2C2 images have been recently released and include surface reflectance and surface temperature products (LST) that have a spatial resolution of 30 and 100 m respectively. Traveling on the descending (daytime) node from north to south, the satellite cross the equator on each pass at a time that provides the maximum illumination with minimum water vapor, crossing the equator at 10:00 a.m. +/- 15 minutes (mean local time).

C. Vectors data

We have used the official land cover map of Córdoba province [13], which contains 21 classes: Dense Forest (1), Scrub (2), Grassland Nat/rocks (3), Shrubland (4), Rock (5), Bare Soil (6), Salina (7), Water body (8), Flood-prone area (9), Water (10), Urban High compactness (11), Urban Medium compactness (12), Urban Low, Compacity (13), Open urban (14), Road infrastructure (15), Annual extensive cultivation (16), Irrigated annual crop (17), Implanted pasture (18), Managed natural pasture (19), Horticultural crops (20), Plantation Forestry (21). It has been built with satellite data from the period 2017-2018 at 1 ha spatial resolution and re-scaled for distribution to 10 m. It is freely available on (https://mapascordoba.gob.ar//descargas). Built-up vector of Córdoba and its metropolitan region, shadow pink in Figure 1, was download from National Geographic Institute (https://www.ign.gob.ar). Surroundings vector, to characterize non urban zones, was created by considering a distance between 7 km and of 15 km from built-up area, as can be seen shadow blue in Figure 1.

D. Image processing

Processing of raster data, vector data, clipping and surroundings vector generation was carried out with the GRASS-GIS open source program [12]. Particularly, the "i.landsat" Toolset to download and process Landsat OLI and TIRS products was used [14]. The temperature quality band was used to mask the pixels with clouds with the i.landast.qa, r.reclass and r.mask tools available in the GRASS-GIS program [12]. The R package "rgrass7", available in R studio software, was then used to import vector and raster data from GRASS and to perform statistical processing and thematic mapping [15]. Finally, QGIS open source program me was used to build maps [16].

Figure 1. RGB LANDSAT 8-OLI image from 28/02/2019, Córdoba city and its metropolitan north-west area (shadow pink), Non urban or surroundings (shadow blue), and dense forest reference site (red dot)

References
Urban Heat Island Intensity and SUHI calculation

Urban Heat Island Intensity calculation: The Urban Heat Island Intensity (UHII) was calculated from the definition given in [8] where the average LST of an urban area minus the average LST of the surrounding area is calculated, equation 1.

\[
UHII = LST_{urban} - LST_{surr}
\]  

Calculation of SUHI index: Equation 2 presents the calculation of the Surface Urban Heat Island Index (SUHI) at a pixel level, where \( LST_i \) is the surface temperature of a pixel and \( LST_{DenseForest} \) is the average surface temperature of an area covered by dense forest. A vector was generated in Google Earth over an area of La Calera Reserve that showed high forest cover, see red dot in Figure 1. Its value is the surface temperature difference between the land block classes and forestland/dense trees, which is used in urban temperature studies [11].

\[
SUHI_i = LST_i - LST_{DenseForest}
\]  

III. RESULTS

A. Heat island analysis

In this analysis we distinguish two regions, Non-urban (surroundings) and Urban, defined as explained in materials and methods section. Figure 2 shows thematic maps corresponding to the mean (\( LST_{average} \)) and standard deviation (\( LST_{sddev} \)) values for each region.

It is observed that the mean value of the Urban region is higher than that of the Non-Urban region, while the standard deviation is lower in the Urban region than in the Non-Urban region. This could be related to a greater homogeneity of land cover classes in the Urban region. Table I presents descriptive statistics for both regions. It can be seen that the maximum value of the two zones is located in the Urban region, while the minimum in the Non-urban region, as should be expected. It can also be seen that the difference between mean LST values, HI, is equal 4.5 °C. Table I presents the values of the descriptive statistics for each region as well as the difference between them. According to climatology registers from "Observatorio" weather station located in Córdoba city, for the period 1981-2010, maximum mean temperature expected for February months is 29.6 °C [17]. However, during 2019 year there were days with 40 °C since it was one of the hottest years of the millennium [18]. In this study we see a maximum value for urban zone equal to 50.9 °C, which is not trustworthy and should be interpreted carefully in terms of emissivity and atmosphere error sources.

Figure 3 presents a box plot of LST for the whole study area (non urban, surroundings and middle zone), urban region and surroundings. It can be seen that the boxes are completely separated for the Urban and Non-urban region. To determine if the differences in means are significant, a Student’s t-test was performed and a p<0.001 was obtained. This indicates that the difference in mean temperature between the urban and non-urban region is significant and equal to 4.5 °C, as indicated above.

\[
\text{LST} °C, 22-02-2019
\]

B. Surface urban heat index

According to Equation 2, the heat island index can be calculated, at a pixel level, by taking into account the surface temperature value minus the average temperature value corresponding to a dense forest measured in the same satellite scene, on the same day. Based on this definition, the average value of an area corresponding to dense forest (red dot in
Table II

| SUHI°C | MEAN | MAXIMUM | MINIMUM | MEDIAN | SD |
|--------|------|---------|---------|--------|----|
| URBAN  | 5.5  | 21.2    | -2.4    | 5.8    | 2.4|
| Non URBAN | 1.0  | 18.1    | -8.5    | 0.6    | 2.4|
| Difference | 4.5  | 3.1     | 6.8     | 8.0    | 0.0|

Figure 1) was calculated and a value equal to 29.7 °C was obtained.

Table II presents the SUHI index, surface urban heat island index, for the Urban and Non-Urban zones. It can be seen that the average SUHI index is 5.5 °C for the urban zone, one degree higher than the previous approximation. In addition, it is observed that the surroundings or non-urban zone presents a SUHI equal to 1.0, when it should be equal to zero if it were equivalent to the behaviour of a dense forest. This may be due to the inclusion of classes other than dense forest within the "Non-urban" region. As it is expected, differences between LST and SUHI index statistics are equal, since the mathematical operation done over images was adding a negative constant (-29.7 °C).

C. Spatial analysis

Figure 4 presents SUHI index maps with 100m spatial resolution, for the whole Study Area (left), the Non-urban (central) region and the Urban region. It can be seen more than five degrees in average greater than dense forest for urban zone.

Figure 5 presents the standard spatial anomaly map of the SUHI index, calculated as the differences between LST of each pixel and LST spatial average, all divided by the spatial standard deviation. Values up to six times the standard deviation are observed in both the Urban and Non-Urban zones. These coincide with compact built-up areas. The spatial patterns are then analysed according to land cover in next section.

D. Land use influence in LST

Figures ?? corresponds to land use map for Urban and the Non-urban regions. It can be seen that urban zone presents mainly red colors while Non-urban region shows more classes related to dense forest, natural grassland and shrub land. TableIII presents the percent of land cover class for each region and mean temperature analysis for each class with respect to urban and non urban regions.

It can be seen that the highest temperature values correspond to urban soils with high, medium, low, shrub and bare soil compactness, which are in much higher proportion in the Urban region. This is in agreement with what was found in the SUHI index for the Urban and Non-Urban regions. However, it is important to note that there are appreciable differences between the two Temperature columns. The difference between the temperature in urban and non-urban areas was then calculated for each land use class and was statistically different from zero (paired samples t-test p=0.0002). It was observed 2 °C on average greater for urban zone than for surroundings, for the same class of land cover. This leads to the conclusion that the same type of land use has different thermal behaviour depending on whether it is located on an urban island (which generates a heat island) or in a rural or open environment. It is important to clarify that the elevation factor was not taken into account in this analysis, and given the topography of the city of Cordoba it is important to carry it out in order to discard or include this cofactor. Although level 2 LST product were not validated for urban and non urban areas of the study zone with field measurements, it is worth to mention that it was successfully validated for water surface temperature 30 km away from Córdoba city in a recent work [?].

IV. CONCLUSIONS AND FUTURE WORK

The use of the satellite data and open source GIS programs allowed for a high-resolution spatial analysis of the urban heat island phenomenon and the spatial distribution of SUHI index in Córdoba city and its surroundings. The methodology used allowed cross-referencing of information between raster and vector data, and in this way it was possible to verify that the thermal behaviour of the same land cover depends on whether...
Table III
LAND COVER CLASSES, ID, PERCENTAGE OF LAND COVER CLASS FOR STUDY AREA, URBAN ZONE, NON URBAN ZONE AND MEAN LST FOR URBAN AND NON URBAN ZONE FOR EACH CLASS.

| CLASS                       | ID | STUDY AREA | % URBAN | % Non URBAN | Temperature Urban | Temperature Non-Urban |
|-----------------------------|----|------------|---------|-------------|-------------------|-----------------------|
| Monte (Dense Forest)        | 1  | 8.27       | 4.45    | 10.66       | 30.58             | 28.91                 |
| Scrub                       | 2  | 16.65      | 3.55    | 15.91       | 34.27             | 30.41                 |
| Grassland Nat/rocks         | 3  | 5.24       | 0.37    | 6.88        | 31.13             | 30.64                 |
| Shrubland                   | 4  | 5.80       | 0.00    | 0.47        | 35.84             | 30.52                 |
| Rock                        | 5  | 0.95       | —       | 0.00        | -                 | 31.58                 |
| Bare Soil                   | 6  | 0.11       | 0.97    | 0.21        | 36.09             | 35.31                 |
| Salina                      | 7  | —          | —       | —           | —                 | —                     |
| Water body                  | 8  | 0.29       | 0.04    | 0.86        | 33.07             | 26.26                 |
| Flood-prone area            | 9  | 0.01       | 0.00    | —           | 35.78             | —                     |
| Watercourse                 | 10 | 0.58       | 1.08    | 0.53        | 33.17             | 30.34                 |
| Urban High compactness      | 11 | 1.37       | 39.36   | 0.56        | 36.29             | 32.91                 |
| Urban Medium compactness    | 12 | 1.15       | 20.05   | 1.53        | 35.37             | 32.69                 |
| Urban Low Compacity         | 13 | 1.15       | 8.12    | 2.54        | 33.38             | 31.97                 |
| Open urban                  | 14 | 0.65       | 12.50   | 0.88        | 34.82             | 31.49                 |
| Road infrastructure         | 15 | 0.81       | 2.69    | 1.03        | 35.84             | 32.61                 |
| Annual extensive cultivation| 16 | 49.69      | 1.01    | 50.07       | 33.08             | 30.80                 |
| Irrigated annual crop       | 17 | —          | —       | —           | —                 | —                     |
| Implanted pasture           | 18 | 0.76       | 0.15    | 0.32        | 33.81             | 33.30                 |
| Managed natural pasture     | 19 | 5.76       | 3.74    | 7.23        | 35.22             | 32.28                 |
| Horticultural crops         | 20 | 0.29       | 1.91    | 0.21        | 35.44             | 37.08                 |
| Plantation Forestry         | 21 | 0.44       | —       | 0.089       | —                 | 29.46                 |

it is located in an urban area or in open areas. This work opens up new possibilities for future temporal studies at the urban scale and the evaluation of the effect of co-factors such as terrain elevation, among others. In future works we will perform validation studies with field data in order to carry out spatio-temporal studies of SUHI index, over Córdoba city and its surroundings, for the period 1984-2021 by means of LANDSAT (TM-TIRS) collection.

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