Temporal analysis of net radiation in the metropolitan area of San Luis Potosí - México using landsat 5 and 8 satellite images

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Abstract. The San Luis Potosí Valley is a basin situated in the municipalities of San Luis Potosí and Soledad de Graciano Sánchez belonging to the San Luis Potosí State and which make up the metropolitan area. This state is located in the north-central zone of México; it has a territorial extension of 64,165 m² that represents 3.12% of the national territory. It is bounded to the north by the states of Coahuila, Nuevo Leon and Tamaulipas; to the south by Guanajuato, Queretaro and Hidalgo; to the east by Veracruz and to the west by Zacatecas and Jalisco. The analysis of the radiation capture phenomenon was carried out in the San Luis Potosí Metropolitan Area (ZMSLP). The study area is located between latitudes 22° 20’ 00” and 22° 02’ 00” north and longitudes 101° 12’ 00” and 100° 44’ 00” west. Net radiation is the phenomenon in which radiation fluxes interact between atmosphere and the earth's surface. This phenomenon leads to processes such as evapotranspiration and photosynthesis. The net radiation analysis can be performed by three methods: (a) by using radiation monitoring stations, (b) by statistical models using data from meteorological stations such as temperature and relative humidity, and (c) by using satellite imagery. Since satellite images offer the possibility of analyzing large tracts of land, this method has been chosen to carry out the study using two images per year, one for the dry season and one for the rainy season between 1990 and 2017. The results show a considerable reduction in net radiation between the study periods, possibly due to the metropolitan area growth that impacts on the environment and therefore to the processes mentioned above.

1. Introduction
The San Luis Potosí Valley covers an area of 1,980 km² and is situated in the central area of the San Luis Potosí State in Mexico, with a population of more than 1,547,000 inhabitants. It covers the San Luis Potosí and Soledad de Graciano Sánchez Municipality and partially the municipalities of Mexquitic de Carmona, Cerro de San Pedro, and Zaragoza. This valley is located on a plain between the San Miguelito mountain range to the west and the Alvarez mountain range to the east with direction from north to south and belongs to Madre Oriental mountain range of the Mexican Republic, forming an endorheic basin that are the basins that have no fluvial outlet to the ocean. The climate for the San Luis Valley is temperate dry, warm temperate desert in the northern metropolitan area and semi-dry temperate
in the south. Rainfall is between 300mm and 400mm per year, with the rainy season occurring from May to October.

Solar radiation is a terminology for the energy flow produced by the sun in the form of electromagnetic waves, due to its behavior is classified as direct, diffuse and reflected [7]. The energy amount that reaches the surface depends on factors such as latitude and altitude, with the equator area being where most radiation is received. Due to its geographical location, Mexico receives radiation greater than 5 Kwh/m2/d [3], which can be favorable when talking about renewable energies. On the other hand, such amounts of solar radiation can be harmful to various health conditions such as skin cancer. The estimation of solar radiation is carried out using data from meteorological stations and other radiation collection equipment, being a disadvantage if sufficient stations are not available. The flux that exists amongst the atmosphere and earth's surface is known as net radiation (NR), and is defined as the difference between descending and ascending short and long wave radiation fluxes [10] and leads the evapotranspiration processes and photosynthesis [5].

Its measurement is uncommon and is only applied in specific cases because of the high cost of both the type of sensor and its handling [8]. Short wave surface radiation (SWNR) is defined as the difference among the short-wave radiation incident on the surface and the reflected short-wave radiation to the atmosphere [13], while long wave surface radiation is defined as the difference between downward and upward long wave radiation [12]. Variations in net radiation are subject to atmospheric conditions such as clouds, temperature, spatial and temporal conditions [9]. It can be determined by direct measurement (radiometers) or by calculations (statistical models, remote sensing techniques) [2], with applications in fields such as hydrology, agriculture, climate research, renewable energies, agrometeorology, irrigation, environmental engineering, etc. [4]. Continuous technological advances in the field of Remote Sensing make these methods ideal for diagnosing NR, as they provide information with high spatial resolution at low cost [10].

The San Luis Potosi Valley is an area that has recently experienced a considerable increase in temperature. Likewise, the heat islands phenomenon has become present. Based on the above, the main objective of this work is to carry out a temporal analysis of the NR present in the San Luis Potosi Valley, Mexico using Landsat 5 and 8 satellite images. This may be useful in determining what role RN plays in regulating climate in the urban area of the Valley. For this study, the methodology proposed by Allen and Collaborators (2007) was applied.
2. Methodology

2.1 Material and Method

To analyze the radiation phenomenon, a Digital Elevation Model (DEM) obtained from the National Institute of Statistics and Geography (INEGI) with a resolution of 30 mt was used, as well as satellite images, of which some details are described; Landsat 5 was established in 1984 with the Thematic Mapper TM sensor, containing seven bands consists of visible spectrum (VIS), Near Infrared (NIR), Short Wave Infrared (SWIR) and the thermal band. Landsat 8 was launched in 2013 with 2 instruments on board: (1) Operational Land Imager (OLI) comprises of nine bands in the visible, near infrared and near infrared short-wave spectrum; and (2) the thermal infrared sensor (TIRS) consists of 2 spectral bands in the long wave infrared (LWIR) region [11]. Both have a spatial resolution of 30 meters and a temporal resolution of 16 days (Table 1).

**Table 1.** Thematic Mapper (TM) (Landsat 5) and Operational Land Imager (OLI) and Thermal Infrared Sensor (TIRS) (Landsat 8) spectral bands.

| Landsat 5 | Spectral Band | Wavelength (µm) | Spatial Resolution (m) |
|-----------|---------------|-----------------|------------------------|
| Band 1 – Blue | 0.45 – 0.52  | 30              |
| Band 2 – Green | 0.52 – 0.60  | 30              |
| Band 3 – Red | 0.63 – 0.69  | 30              |
| Band 4 – Panchromatic | 0.76 – 0.90 | 30              |
| Band 5 – SWIR 1 | 1.55 – 1.75 | 30              |
| Band 6 – Thermal | 10.40 – 12.50 | 30            |
| Band 7 – SWIR 2 | 2.08 – 2.35  | 30              |

| Landsat 8 | Spectral Band | Wavelength (µm) | Spatial Resolution (m) |
|-----------|---------------|-----------------|------------------------|
| Band 1 – Coastal/Aerosol | 0.432 – 0.451 | 30              |
| Band 2 – Blue | 0.452 – 0.512 | 30              |
| Band 3 – Green | 0.533 – 0.590 | 30              |
| Band 4 – Red | 0.636 – 0.673 | 30              |
| Band 5 – NIR | 0.851 – 0.879 | 30              |
| Band 6 – SWIR | 1.566 – 1.651 | 30              |
| Band 7 – SWIR | 2.107 – 2.294 | 30              |
| Band 8 – Panchromatic | 0.503 – 0.676 | 30              |
| Band 9 – Cirrus | 1.363 – 1.384 | 30              |
| Band 10 – LWI | 10.60 – 11.19 | 100             |
| Band 11 – LWI | 11.50 – 12.51 | 100             |

In this analysis, 10 Landsat 5 images acquired between 1990 and 2009 and 4 Landsat 8 from 2015 and 2017 were used, with path/row 28/45 available in "Earth Explorer" (https://earthexplorer.usgs.gov/), for each year the image corresponding to the rainy and dry season was acquired. Detailed information can be found in Table 2.

**Table 2.** Image dataset used in this study.

| Acquisition Date | Season | Time | Product | Platform |
|------------------|--------|------|---------|----------|




2.2 Image pre-processing

The images obtained were converted from digital number (DN) to radiance values (radiometric correction). For this process we used the Chander method and collaborators [6] which use radiance scale factors which are provided in the metadata:

\[
L_\lambda = M_L \times Q_{cal} + A_L
\]

In which:

- \( L_\lambda \) = radiance at the atmosphere roof (TOA) (W / (m² srad µm)).
- \( M_L \) = multiplicative reescalation factor for each band (W / (m² srad µm)).
- \( A_L \) = additive reescalation factor for each band (W / (m² srad µm)).
- \( Q_{cal} \) = digital number (DN).

2.3. Net radiation

Net radiation is terminology for the energy flow from the sun and the earth's surface [10]. It is counted by extracting the incoming short wave and long wave radiation and the outgoing long wave radiation [1] by using the following equation:

\[
R_n = R_{s\downarrow} - \alpha R_{s\downarrow} + R_{L\downarrow} - R_{L\uparrow} - (1 - \varepsilon_0)R_{L\downarrow}
\]

In which \( R_{s\downarrow} \) is the incident shortwave radiation (W m⁻²); \( \alpha \) is the superficial (dimensionless) albedo; \( R_{L\downarrow} \) is the incident long wave radiation (W m⁻²); \( R_{L\uparrow} \) is the reflected long wave radiation (W m⁻²); and \( \varepsilon_0 \) is broad band (dimensionless) surface thermal emissivity. The term \((1 - \varepsilon_0)R_{L\downarrow}\) represents the incident long wave fraction reflected from the Earth's surface.
2.3.1. Incident wave radiation. It is the difference between the incident short wave radiation (W m$^{-2}$) on the earth’s surface and the short-wave radiation reflected to the atmosphere and this parameter is calculated with the following equation:

$$ R_{s↓} = \frac{G_{SC} \cos \theta_{rel} \tau_{\omega}}{d^2} $$

(1)

Where $G_{SC}$ is the constant of solar (1367 W m$^{-2}$), $\theta_{rel}$ is the solar incidence angle, $d^2$ is the relative distance between the earth and the sun, and $\tau_{\omega}$ is transmissivity of the atmosphere, which is calculated by the function:

$$ \tau_{\omega} = 0.35 + 0.627 \exp \left[ -0.00146 P \frac{K_t \cos \theta_{hor}}{293} - 0.75 \left( \frac{W \cos \theta_{hor}}{\cos \theta_{hor}} \right)^{0.4} \right] $$

(2)

Where $P$ is the pressure of atmospheric (Kpa), W is the water content in the atmosphere (mm), and $\theta_{hor}$ is the zenithal solar angle on a horizontal surface. $K_t$ corresponds to a turbidity coefficient of 0 < $K_t$ < 1, in which $K_t = 1.0$ is used in areas with clean air, while $K_t = 0.5$ is used in areas with extreme turbidity, dust, or polluted air. $P$ is obtained by using a Digital Elevation Model (DEM) and applying the following formula:

$$ P = 101.3 \left( \frac{293 - 0.0065 z}{293} \right)^{5.26} $$

(3)

Where 293 is the air temperature standard (K), $z$ is the altitude above sea level (m). $W$(mm) is obtained from near-surface vapour pressure data, which are obtained from meteorological stations within the study area by applying this formula:

$$ W = 0.14 e_a P_{air} + 2.1 $$

(4)

Where $e_a$ is the vapour pressure near the surface obtained from the dew point (Pr)

$$ e_a = 0.611 \exp \left( \frac{17.27 Pr}{Pr + 237.3} \right) $$

(5)

The solar incidence angle is defined as the angle exist between the solar beam and a vertical line perpendicular to the earth’s surface. The slope and aspect are extracted from the DEM and the following formula is applied:

$$ \cos \theta_{rel} = \sin(\delta) \sin(\phi) \cos(s) - \sin(\delta) \cos(\phi) \sin(s) \cos(y) + \cos(\delta) \cos(\phi) \cos(s) \cos(\omega) + \cos(\delta) \sin(\phi) \sin(s) \cos(y) \cos(\omega) + \cos(\delta) \sin(y) \sin(s) \sin(\omega) $$

(6)

Where $\delta$ is the earth declension (positive during summer in the northern hemisphere); $\phi$ is the pixel latitude; $s$ is the slope where $s = 0$ means horizontal slopes and $s = \pi/2$ means vertical slopes; $y$ is the surface appearance; $\omega$ is the hour angle. All trigonometric equations are handled in radians. Parameter $d^2$ is obtained as a day of the year function (DOY) with the equation:
2.3.2 Surface albedo. It is the quantity of radiation that is reflected by the earth's surface; it is a biophysical characteristic that regulates net radiation. Its value varies according to the coverage present in the study area, and in some cases, a low albedo value (as it is in the case of urban coverage) represents an increase in temperature. It is estimated by adding the bands reflectance within the spectrum of short wave using the following formula:

$$ d^2 = \frac{1}{1 + 0.033 \cos(DOY \pi/365)} $$

(7)

Where $W_b$ is the weighting coefficient representing the solar radiation fraction on the surface that occurs within the spectral range in a determined band (Table 3), and $n$ is the number of bands that make up the satellite.

| Coefficient | Band 1 | Band 2 | Band 3 | Band 4 | Band 5 | Band 7 |
|-------------|--------|--------|--------|--------|--------|--------|
| $W_b$       | 0.254  | 0.149  | 0.147  | 0.311  | 0.103  | 0.036  |

2.3.3 Reflected long wave radiation. It is surface driven radiation produced by temperature and emissivity of it, to obtain it is used the Stefan - Boltzmann equation:

$$ R_L = e_0 \sigma T_s^4 $$

(9)

Where $e_0$ is the surface emissivity (dimensionless); $\sigma$ is Stefan Boltzmann constant ($5.67 \times 10^{-8}$ $\text{Wm}^{-2} \text{K}^{-4}$); and $T_s$ is the temperature of surface (K). The surface emissivity is estimated using the following equation:

$$ e_0 = 0.95 + 0.01 \text{LAI cuando LAI} \leq 3 $$

$$ e_0 = 0.98 \text{cuando LAI} > 3 $$

(10)

In which LAI (Leaf Area Index, measured in $\text{m}^2 \text{m}^{-2}$) represents the relationship between the total surface leaf area per unit area of land. This index is a measure of biomass and resistance of canopy to steam flow and it is obtained by applying the following equation:

$$ \text{LAI} = -\ln[(0.69 - SAVI_{ID})/0.59]/0.91 $$

(11)

Where SAVI is the Soil Adjusted Vegetation Index that is obtained from the function:

$$ SAVI = \frac{(1 + L)(\rho_{tA} - \rho_{t3})}{L + (\rho_{tA} + \rho_{t3})} $$

(12)

Where $L$ is a constant to minimize soil biases and for this specific case 0.1 was used, and the variables $\rho_{tA}, \rho_{t3}$ correspond to the atmospheric reflectances of bands 3 and 5 for Landsat 5 TM and bands 4 and 5 for Landsat 8 OLI.
The temperature of surface is calculated by applying the modified Plank equation, which includes atmospheric corrections and surface emissivity:

\[ T_s = \frac{K_2}{\ln[(\varepsilon_{NB} K_1/R_c) + 1]} \]  

(13)

Where \( \varepsilon_{NB} \) corresponds to the short-wave emissivity of the satellite thermal sensor (band 6 for Landsat 5 and bands 10 and 11 for Landsat 8 TIRS); \( R_c \) is the fixed thermal radiance of the surface, which is obtained from the spectral radiance of the thermal bands. Constants \( K_1 \) and \( K_2 \) are \( K_1 = 607.8 \) and \( K_2 = 1261 \) Wm\(^{-2}\)sr\(^{-1}\)μm\(^{-1}\) for Landsat 5, for Landsat 8 constants \( K_1 \) and \( K_2 \) correspond to bands 10 and 11 found in the metadata file. \( R_c \) is calculated with the function:

\[ R_c = \frac{L_{t,6} - R_p}{\tau_{NB}} - (1 - \varepsilon_{NB}) R_{sky} \]  

(14)

In which \( L_{t,6} \) is the spectral radiance of the thermal bands (Wm\(^{-2}\)sr\(^{-1}\)μm\(^{-1}\)); \( R_p \) is the radiance path at length 10.4 - 12.5 μm Wm\(^{-2}\)sr\(^{-1}\)μm\(^{-1}\); \( R_{sky} \) is the short-wave thermal radiation in clear sky conditions and \( \tau_{NB} \) is the transmissivity of air in the length range 10.4 - 12.5 μm. \( R_p \), \( \tau_{NB} \) and \( R_{sky} \) requires an atmospheric correction model so the values 0.91, 0.866 and 1.32 respectively given by Allen and collaborators (2007) were used.

Narrow-band transmissivity is calculated from the equation:

\[ \varepsilon_{NB} = 0.97 + 0.0033 \text{LAI, cuando LAI} \leq 3 \]
\[ \forall \varepsilon_{NB} = 0.98 \text{cuando LAI} > 3 \]  

(15)

This transmissivity applies when the Normalized Differential Vegetation Index (NDVI) is greater than zero, when the NDVI is less than or equal to zero, \( \varepsilon_{NB} \) gets the value of 0.985. The NDVI is calculated from the red and near infrared bands, 3 and 4 for Landsat 5 and 4 and 5 for Landsat 8.

\[ NDVI = \frac{\rho_{t,NIR} - \rho_{t,Red}}{\rho_{t,NIR} + \rho_{t,Red}} \]  

(16)

2.3.4 Incident long wave radiation. The incident long wave radiation is atmospheric flux of thermal radiation (Wm\(^{-2}\)) and is calculated by the Stefan-Boltzmann equation:

\[ R_{L1} = \varepsilon_a \sigma T_a^4 \]  

(17)

In which \( \varepsilon_a \) is the effective emissivity of atmosphere (dimensionless) and \( T_a \) is the air temperature near the surface (K). \( \varepsilon_a \) is calculated with the function:

\[ \varepsilon_a = 0.85 \left(- \ln \tau_{sw}\right)^{0.09} \]  

(18)

In which \( \varepsilon_a \) is the broadband atmospheric transmissivity of short-wave radiation derived from equation 17. The parameter \( T_a \) can be replaced by surface temperature \( (T_s) \).
3. Results and Discussions

The appearance and slope of the study area were obtained from the DEM, the radiometric and atmospheric correction of the satellite images was carried out to obtain the Leaf Area Index (LAI), the Soil Adjusted Vegetation Index (SAVI) and the Normalized Difference Vegetation Index (NDVI) for the reflected long wave radiation part and for the albedo calculation. The radiometric correction bands 7 and 11 of Landsat 5 and 8 respectively were used in the surface temperature calculation. This methodology was implemented to the images aims to obtain the net radiation maps for the two seasons (drought and rain). The results of the net radiation diagnosis between 1990 and 2000 are shown in Figure 2, while Figure 3 shows the 2009 Landsat 5 and 2015 and 2017 radiation maps for Landsat 8. As expected in the rainy season, the highest radiation concentration is recorded in the images due to the relationship it has with the atmospheric conditions of the area and it can also be seen that this has decreased considerably due to the area urbanization and the impact it causes on the environment. After completion of the diagnosis values of up to almost 700 W/m2 could be seen with a drop in the measured values in the last two years of the analysis period, this may be due to changes in the region's climate due to weather variability.
Figure 2. Net radiation from the years 1990 (a and b); 1995 (c and d); 2000 (e and f) and 2005 (g and h) of Landsat 5.
4. Conclusions

In this work the net radiation modeling was made using a methodology that is adapted to carry out processes in satellite images, which show a considerable degree of precision in the obtained data. Using Landsat satellite imagery is of great help when analyzing large areas due to the spatial and temporal resolution of Landsat platforms, as studies can be carried out in considerable periods of time, depending on the analysis needs. However, it is important to note that, when performing an RN analysis through remote sensing data, an error may exist if a clean sky image is not available.

On the other hand, the analysis showed that, in areas with totally urbanized roofs, low values are registered in the albedo, which causes an increase in the surface temperature, causing the RN to remain stored in this type of roof and not regulate the environment warming. The results show considerable variation between the results obtained with Landsat 5 and Landsat 8, with higher net radiation measurements in the rainy season.

Figure 3. Net radiation for the years 2009 (a and b) of Landsat 5 and the years 2015 (c and d) and 2017 (e and f) of Landsat 8.
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