Synergy between the Urban Heat Island and the Urban Pollution Island in Mexico City during the Dry Season

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ABSTRACT

The interaction between Urban Heat Island (UHI) and Urban Pollution Island (UPI) is relevant for urban studies as well as for health studies. Both phenomena have not been widely studied in Greater Mexico City (GMC). Therefore, we study the interaction between UHI and UPI in GMC where urban and rural areas are not well defined. Also, long-range transport of pollution affects GMC pollution concentration. We used 5-year data (2015–2019) from weather stations to measure the Air UHI (AUHI) and Landsat 8 data to assess the Surface UHI (SUHI). The Urban Pollution (UP) has been assessed with Particulate Matter PM10 and PM2.5 concentrations measured near the surface by air quality monitoring stations, the Aerosol Optical Depth has been used as a measure of UP. During the dry season (February–May), at night (20:00–07:59 h LT), a positive correlation (statistically significant) between the UHI and UP has been found ($r = 0.39$) for the UPI defined with PM2.5 between the urban and rural stations. Whereas a significant correlation ($r = 0.50$) has been found between UPI defined with PM10 between the urban and rural station during the autumn.

Keywords: Urban heat island, Air quality, Particulate matter, Aerosol Optical Depth, Mexico

1 INTRODUCTION

The Urban Heat Island (UHI) is a well-documented phenomenon that occurs when urban areas are warmer than their surrounding rural areas (Palme, 2021) as a result of accelerated urbanization and land cover changes due to human activities. The UHI is studied because it increases energy consumption (Hirano and Fujita, 2021) and heat can cause negative effects to human’s health and can be related to mortality (de Schrijver et al., 2021).

Another consequence of urbanization and industrialization is the pollution of air which has drastically increased with the growth of urban areas. Particulate Matter (PM) is a major pollutant of urban areas monitored because of the effect it has on human’s health. The sources of PM10 (PM with diameter smaller than 10 micrometers) have been associated to agriculture, burning of biomass, heavy traffic and dust (Mukherjee and Agrawal, 2017). Whereas PM2.5 (PM with diameter smaller than 2.5 micrometers) has been mainly related to traffic, fuel burning and forest fires (Mukherjee and Agrawal, 2017). Therefore, PM2.5 comprises a portion of PM10.

PM is regularly monitored because it causes negative effect in human’s health, especially, respiratory diseases (Zhang et al., 2020), cardiovascular diseases and increased mortality as well as economic hardship to underfunded health systems (Abe et al., 2018). A study in Guadalajara, the second biggest metropolitan area of Mexico, related high PM10 exposure to high mortality rates as the result of respiratory and cardiovascular diseases (Cerón-Bretón et al., 2018). While PM2.5 can penetrate deep into the lung, irritate and corrode the alveolar wall and consequently affect lung
function (Xing et al., 2016; Yang et al., 2020). Also, long term PM$_{2.5}$ exposure can also contribute to driving the initiation and progression of diabetes mellitus (Feng et al., 2016). Pollution concentrations in the air tend to vary in urban and rural areas because of land cover, land use and air circulation. The difference in pollution concentration in an urban agglomeration is known as the Urban Pollution Island (UPI) (Crutzen, 2004). Since high temperatures accelerate certain atmospheric chemistry cycles, most of which lead to enhanced air pollution (Crutzen, 2004), there is an interaction between the intensity of the UHI and the UPI. This interaction has become a major research topic as pointed out by Ulpiani (2021), who reviewed the studies of the interaction between UHI and UPI during the last 30 years (1990–2020). The review found that the interaction between UHI and UPI depends on local topography, geography, climate and local-scale specificities. Most of the studies reviewed are from cities in Europe, The United States of America and Asia (Ulpiani, 2021). Recently, three studies focus on the relation UPI and UHI in Berlin (Li et al., 2018), Beijing (Li et al., 2020), and Seoul (Ngarambe et al., 2021). During the summer in Berlin, a positive correlation has been found between the spatial distributions of the UPI defined from ground-based pollution data and the UHI measured with Land Surface Temperature from satellites. However, the UPI derived from satellite images and the UHI measured from ground-based meteorological data were found to be negatively correlated at night (Li et al., 2018).

In Beijing, Li et al. (2020) found that the correlation between the two phenomena is significantly negative in winter (both, during day- and nighttime) and significantly positive during spring (both, during day- and nighttime) using ground based PM$_{2.5}$ data and Downward Longwave Radiation data. In Seoul, Ngarambe et al. (2021) found that most air pollutants increased with increasing UHI levels and that in autumn, air pollutants and UHI intensity had a stronger correlation. In their study, SO$_2$, NO$_2$, CO, PM$_{10}$ and PM$_{2.5}$ data from Seoul was used.

Previous studies have shown that the relation between UHI and UPI is greater at night than during daytime because at night there are many heat fluxes from the city surface to the atmosphere but pollution particles in the atmosphere stop these fluxes from being released thus, the city heats up (Cao et al., 2016).

The relationship between UHI and UPI is different depending on the pollutant measured, the urban and rural physical characteristics of the city as well as the local climate. Therefore, this study contributes to the understanding of UHI and UPI interaction in one of the most populous cities of the world, Mexico City. Furthermore, studies about urban heat island in Latin-American cities are very scarce or out-of-date (Palme, 2021). One of the first UHI studies in Mexico City used only two meteorological stations (Jauregui, 1997), later studies had only few stations so the spatial distribution of the UHI in Mexico City has not been studied yet. Another contribution of this study is the definition of the spatial distribution of the UHI in Mexico City with remote sensing techniques and data from 2015–2019.

2 DATASET AND METHODS

2.1 Study Area

Mexico City (19.43°N, 99.13°W) according to the latest census in 2020 has 9,210,000 inhabitants (INEGI, 2021) and limits to the north, east and west with the State of Mexico and to the south with the state of Morelos (Fig. 1). Greater Mexico City (GMC) adds some municipalities of the State of Mexico, which are attached to Mexico City with a total population of around 22 million inhabitants in (INEGI, 2021). The city is surrounded by mountains to the west, east and south. It experiences middle latitude systems in the dry season, and it is exposed to tropical interactions during the wet season.

The layout of the city is heterogeneous, meaning that areas depending on land use or land cover are not well defined and they are rather mixed (Fig. S1). In general, the west of city includes low-rise high-density buildings, the city center has mid-rise and mid-density buildings. The south east contains low density low-rise housing, and the east of the city has lots of high-rise buildings. According to official 2019 mobility report (Secretaría de Movilidad, 2019), in the morning most people travel from the municipalities further away from the city to downtown and Eastern business center district. In contrast, from 17:00 h the flux is in the opposite direction, from downtown and business district to Mexico City outskirts (Secretaría de Movilidad, 2019).
2.2 Ground Stations Data

In this study, the Air Urban Heat Island (AUHI) intensity is assessed using meteorological data from weather stations data from the Meteorology and Ultraviolet Radiation Monitoring Network (REDMET) operated by Mexico City Government through the Secretary of Environment (Fig. 1). The Surface UHI (SUHI) is retrieved using LANDSAT 8 imagery (USGS, 2021a) and the concentrations of PM$_{10}$ and PM$_{2.5}$ near the surface are obtained with data from the Automatic Ambiental Monitoring Network (RAMA) (DGCA, 2021a) managed by the local government and used to monitor Air Quality in Mexico City. Finally, the Aerosol Optical Depth (AOD) is retrieved from MODIS data to calculate the PM$_{2.5}$ and PM$_{10}$ atmospheric concentrations.

2.3 Air Temperature Data

The REDMET measures temperature, relative humidity, wind direction and wind speed every hour in 26 locations in GMC (DGCA, 2021b). REDMET has been operating since 1986, in 2015 some stations have gone out of service while new ones started operating in order to cover the whole metropolitan area. Only 9 REDMET weather stations have been chosen (Fig. 1) that coincided with the particle concentration measurements at the same location. Data from 2015–2019 have been processed.

2.4 PM$_{10}$ and PM$_{2.5}$ Data

The RAMA air quality monitoring network reports hourly concentrations of O$_3$, NO$_2$, NO$_x$, NO,
SO₂, CO, PM₁₀ and PM₂.₅ (DGCA, 2021a). 13 stations have been chosen for the period 2015–2019. Three of those stations report both PM₁₀ and PM₂.₅ in urban areas (BJU, MER and HGM), 5 stations report PM₁₀ only (ACO, CUT, CHO, CUA, IZT) and other 5 stations report PM₂.₅ (SFE, NEZ, CAM, CCA, UAX) in urban and rural areas in GMC (Fig. 1). The stations chosen have the least missing values for the period 2015–2019.

2.5 Remote Sensing Data
2.5.1 Land Surface Temperature (LST)
Land Surface Temperature has been obtained using the Operational Land Imager (OLI) and Thermal Infrared Sensor (TIIRS) onboard the LANDSAT 8 satellite (USGS, 2021a). The LANDSAT 8 satellite flies over Mexico City every 16 days at around 16:59 h local time (LT) (UTC-6) and images with less than 30% of cloud cover only were considered.

LST has been calculated from LANDSAT 8 imagery by first calculating the top of atmosphere (TOA) spectral radiance and then by converting it to At-Sensor Temperature (Avdan and Jovanovska, 2016; USGS, 2021b).

$$L_\lambda = M_\ell \times Q_{cal} + A_\ell$$

where $M_\ell$ is a band-specific multiplicative rescaling factor, $A_\ell$ is the band-specific additive rescaling factor, both factors are available from image metadata. $Q_{cal}$ is the band 10 image (spatial resolution of 100 m). Temperature in Kelvin is calculated using Eq. (2).

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

where $K_1$ and $K_2$ are band-specific thermal conversion constants from image metadata. $L_\lambda$ is the previously calculated TOA spectral radiance.

2.5.2 Aerosol optical depth
Aerosols are defined as the blend of liquid and solid suspended particles. These particles can be fog, mist, particulate matter, and dust. Aerosol Optical Depth (AOD) is defined as the integral of vertical aerosol extinction coefficient from the earth surface to the TOA (Ranjan et al., 2021). Therefore, there is a strong positive linear correlation between AOD and air pollutants such as PM₁₀ (Jiménez et al., 2020) and PM₂.₅ (Zhang and Kondragunta, 2021). The greatest concentration of aerosol is near the surface, therefore, AOD can be used to estimate PM concentration near the surface.

The MODIS Terra and Aqua combined Multi-Angle Implementation of Atmospheric Correction (MAIAC) Land AOD at 1 kilometer pixel resolution (Lyapustin and Wang, 2018) data were used to estimate AOD in Mexico City. Previous studies have shown the relation between AOD and PM₁₀ and PM₂.₅ concentrations based on a liner regression model (Kong et al., 2016; Ranjan et al., 2021). However, the coefficients of the linear model have to be empirically determined and change in different locations.

MAIAC data were used because the 1-km pixel resolution makes it ideal to study aerosol concentrations in different areas of the city. Another reason for using MODIS, is that it overpasses GMC twice a day, so there is a good amount of data available. We collected and processed MAIAC data for February, March, April and May 2015–2019 and April 2020 using Google Earth Engine (Gorelic et al., 2017).

3 RESULTS
3.1 Classification of Urban and Rural Areas in GMC
The air quality monitoring and meteorological stations (Fig. 1) were classified as urban and
rural stations based on land cover and weather patterns to measure the Urban Heat Island intensity and the PM concentrations around the city. A classification for urban temperature studies has been suggested by Stewart and Oke (2012), however, the urban areas defined in that classification are not clearly defined in Mexico City due to the unplanned grow of the city. Previous UHI studies in GMC have only used two meteorological stations to define the UHI based on ground-based-meteorological data, one in Tacubaya and one in Mexico City Airport (Jauregui, 1997). Also, the weather stations from Mexico's Meteorological Service (SMN) and Radiosonde in Tacubaya and at the airport have been used to study the UHI in Mexico City metropolitan area (Vargas and Magaña, 2020). In the first study the station at the airport was classified as “rural”; however, in the last study, stations further away from the city center have been classified as rural. Even though both articles examine the UHI in GMC, they do not study the spatial distribution of the UHI due to the low number of weather stations used.

Since, there is no official classification of meteorological stations in GMC, we have grouped meteorological and air quality monitoring stations in three groups, rural stations, semi-urban stations and urban stations. Rural areas were defined as areas with lower population and few roads with many open vegetation spaces and industrial or agricultural activities (Fig. S2). Semi-Urban areas have a few built structures (or low population density), and they have some greenery, typically the land use is residential and commercial. Semi-urban areas are mostly found in the southern and eastern part of the city. Urban areas have been defined as areas where there are many built structures (or there is a high population density) and roads with heavy traffic, moreover, only few green areas are found in urban areas; therefore, most anthropogenic sources of heat and PM are in urban areas (Fig. S2). Table 1 shows the classification of stations used in this study.

Some stations in Table 1 report PM and meteorological data while others only report particle concentrations. PM$_{2.5}$ is measured at the SFE, NEZ, CAM, CCA and UAX stations and PM$_{10}$ is measured at the ACO, CUT, CHO, CUA and IZT stations, and only three stations (BJU, MER and HGM) report both PM$_{10}$ and PM$_{2.5}$. The rural stations are mainly located in the north of GMC (Fig. 1).

3.2 Climatology and PM Concentration Patterns

Mexico City’s climate is classified as Cwb in Köppen-Gaiger scale (Peel et al., 2007) which is defined as subtropical highland variety with the following characteristics $T_{\text{hot}} > 10^\circ\text{C}$ and $0^\circ\text{C} < T_{\text{cold}} < 18^\circ\text{C}$, $P_{\text{dry}} < 40\text{ mm}$ and $P_{\text{dry}} < P_{\text{wet}}/3$, $T_{\text{mon10}} \geq 4$ where $T_{\text{hot}}$ is the temperature of the hottest month, $T_{\text{cold}}$ is the temperature of the coldest month, $P_{\text{dry}}$ is precipitation of the driest month in summer, $P_{\text{wet}}$ precipitation of the wettest month in the winter and $T_{\text{mon10}}$ is the number of months where the temperature is above $10^\circ\text{C}$. Due to the high altitude of the city, the weather is mild, there are two main seasons, the dry season when rain is scarce and the wet season when 90% of total annual rainfall (monsoon regime). Dry season is from October to May. Wet season is from June to September. In terms of air quality, during the dry season the concentrations of both, PM$_{2.5}$ and PM$_{10}$ are greater than during wet season when rain washed up the pollutants in the air.

3.2.1 Temperature pattern in GMC

The diurnal cycles and monthly averages of temperature, PM$_{10}$ and PM$_{2.5}$ obtained with data from 2015–2019 from RAMA and REDMET are shown in Fig. 2. The monthly average temperature in urban stations is greater than in semi-urban and rural stations (Fig. 2). Moreover, April and May are the hottest months of the year, in contrast, January is on average the coldest month of the year. During rainy season the temperatures tend to be lower. The average diurnal cycle of temperature in GMC in Fig. 2 shows that the warmest time of the day is from 14:00 to 16:00 h LT whereas the coldest hour of the day is at 07:00 h LT. Urbanization generates a temperature contrast with the rural region throughout the annual cycle. The greatest contrast occurs during dry periods (~3°C), particularly in the period of October, November and December (~4°C), where in the rural area there is still abundant healthy vegetation. From January on, this vegetation tends to disappear and bare soil and dry vegetation predominate. UHI occurs throughout the diurnal cycle, however the greatest temperature contrasts are found in the early morning (00:00–10:00 LT).
Table 1. Classification of stations.

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Code</th>
<th>Location</th>
<th>Elevation [m.a.s.l]</th>
<th>Classification</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Meteorological data</td>
<td>PM$_{10}$</td>
<td>ACO</td>
<td>2198</td>
<td>Rural</td>
<td>Low population density, open spaces, agricultural and industrial activities, a highway is nearby. Industrial and agricultural vehicles</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Cuautitlán</td>
<td>2263</td>
<td>Rural</td>
<td>Low population density, industrial warehouses, at least two major highways nearby. Heavy industrial traffic</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Chalco</td>
<td>2253</td>
<td>Semi-urban</td>
<td>High population density, a body of water nearby, two main highways nearby. Residential, commercial, and industrial activities</td>
</tr>
<tr>
<td>No Meteorological data</td>
<td></td>
<td>Cuajimalpa</td>
<td>2704*</td>
<td>Semi-urban</td>
<td>Mid-density, residential area, with open and green areas. Low traffic.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Iztacalco</td>
<td>2238</td>
<td>Urban</td>
<td>High population density, busy streets, no green areas. Residential and commercial area with heavy traffic</td>
</tr>
<tr>
<td>Meteorological data</td>
<td>PM$_{2.5}$</td>
<td>Santa Fe</td>
<td>2599*</td>
<td>Semi-urban</td>
<td>Low population density, High-rise buildings with open spaces and green areas. Commercial area with heavy traffic</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Nezahualcóyotl</td>
<td>2235</td>
<td>Urban</td>
<td>High population density, low rise buildings, residential, commercial, and industrial activities. Heavy traffic, low access to green areas</td>
</tr>
<tr>
<td>No meteorological data</td>
<td></td>
<td>Camarones</td>
<td>2233</td>
<td>Urban</td>
<td>High population density, mid-rise buildings, residential, commercial, and industrial activities, heavy traffic</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Centro de Ciencias de la Atmósfera</td>
<td>2280</td>
<td>Semi-urban</td>
<td>Inside UNAM’s** 773 hectares campus, with big open spaces and green areas. Low traffic. Only research and teaching activities happen in the campus. Surrounded by a high density residential (low rise) area and a low density (low rise) residential area</td>
</tr>
<tr>
<td></td>
<td></td>
<td>UAM Xochimilco</td>
<td>2246</td>
<td>Rural</td>
<td>Inside UAM*** campus, big open spaces, green areas, a body of water nearby. Only research and teaching activities happen in the campus. Surrounded by low-density (low-rise) buildings</td>
</tr>
<tr>
<td>Meteorological data</td>
<td>PM$<em>{10}$ and PM$</em>{2.5}$</td>
<td>Benito Juárez</td>
<td>2250</td>
<td>Urban</td>
<td>High population density, near a city park, surrounded by mid-rise buildings, heavy traffic. Residential and commercial areas</td>
</tr>
<tr>
<td></td>
<td></td>
<td>La Merced</td>
<td>2234</td>
<td>Urban</td>
<td>High density, near a big market, surrounded by mid-rise buildings, heavy traffic. Commercial area</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Hospital General de México</td>
<td>2245</td>
<td>Urban</td>
<td>High density, surrounded by high-rise and mid-rise buildings. Heavy traffic. Residential and commercial zones</td>
</tr>
</tbody>
</table>

* The effect of elevation has been compensated using temperature gradient with height 6.5°C km$^{-1}$.  
** National Autonomous University of Mexico.  
*** Metropolitan Autonomous University.  
m.a.s.l: Meters above sea level.
3.2.2 PM$_{10}$ concentration pattern

From January to April, PM$_{10}$ concentrations in rural areas are on average 5 µg m$^{-3}$ higher than in the other areas due to agricultural activities, biomass burning, and heavy industrial traffic during the winter (Fig. 2). These sources were also identified by (Mukherjee and Agrawal, 2017) at global scale. In contrast, from May to December, PM$_{10}$ concentration in urban areas is greater than in rural and semi-urban stations because of the change in vegetation cover in rural regions during the rainy season.
In the early morning hours, around 06:00 to 09:00 h LT, PM\textsubscript{10} concentration in rural areas is the highest, on average 70 µg m\textsuperscript{-3}, due to the low boundary layer height (~500 m) (García-Franco \textit{et al.}, 2018) and air stagnation conditions, trapping particles near the surface. From 10:00 to 16:00 h LT, PM\textsubscript{10} concentration is higher in urban areas than in rural areas caused by traffic and other anthropogenic sources that emit particles to the atmosphere. During the daytime, the concentration of PM\textsubscript{10} in rural areas decreases due to convective plumes generated as the sun warms up the surface and ventilation conditions clean the atmosphere by dilution of air and pollutants that lower emission concentration near the surface. Moreover, some events of long-range transport of pollutants from other parts of the country, especially from Tula, Hidalgo, contribute to an increase in PM\textsubscript{10} concentration in the urban area (García-Escalante \textit{et al.}, 2015). Finally, at night, from 02:00 to 06:00 h LT PM\textsubscript{10} concentration is on average the same (30 µg m\textsuperscript{-3}) in all areas. In December and January, there is nearly no dust as most of the rural areas are still “green”, and during these months there are no local rural sources of PM\textsubscript{10}.

The greenery available from October to December is greater than from February to May, based on the Normalized Difference Vegetation Index NDVI (Fig. S3). Therefore, focus is given to the relation between UPI and UHI from February to May when local sources and aerial transportation contribute to increased PM\textsubscript{10} concentrations due to the bare soil conditions in the rural areas. Therefore, different results to previous studies are expected such as in Berlin (Li \textit{et al.}, 2018) where the urban and rural areas are clearly defined, and pollution sources are unique to each region.

3.2.3 PM\textsubscript{2.5} concentration pattern

PM\textsubscript{2.5} concentrations are higher in urban areas throughout the year and from 07:00 to 18:00 h LT (Fig. 2) because PM\textsubscript{2.5} sources are mostly anthropogenic or related to industrial activity and intense traffic conditions. In GMC, traffic, industrial and other anthropogenic sources are active during the working hours of 08:00 to 17:00 h LT. Therefore, the PM\textsubscript{2.5} concentration increases at that time. The diurnal cycle of PM\textsubscript{2.5} concentrations in GMC (Fig. 2) follows similar patterns to stations in North America and the world (Manning \textit{et al.}, 2018). Monthly PM\textsubscript{2.5} concentration reaches its maximum values from November to February because the lack of dilution during 10:00 to 14:00 h LT period. In addition, only during April, May and June, PM\textsubscript{2.5} concentration in semi-urban areas is higher than in rural areas, whereas the rest of the year concentration in urban and semi-urban are on average the same (Table 1).

3.3 The Urban Heat Island

3.3.1 Air Urban Heat Island (AUHI) intensity

The AUHI Intensity (AUHII) is measured using REDMET data from urban stations previously described (Fig. 1 and Table 1) and subtracting the temperature in semi-urban and rural areas.

\[ AUHII_{\text{rural}} = T_{\text{urban}} - T_{\text{rural}} \]  \hspace{1cm} (3)

\[ AUHII_{\text{semi-urban}} = T_{\text{urban}} - T_{\text{semi-urban}} \]  \hspace{1cm} (4)

AUHII in Mexico City has been assessed with data from February to May from 2015–2019 because during this period temperatures are high and PM concentrations are also high due to the dry and rural bare soil conditions (Fig. 2 and Fig. S3).

The average AUHII\textsubscript{rural} during February and March reaches higher values and decreasing afterwards (Fig. 3(a)), in March it reaches on average 2.5°C. In terms of the diurnal cycle (Fig. 3(b)), the maximum intensity happens at 07:00 h LT, with 3.4°C, the temperature difference decreases during the day, and it increases again from 16:00 h LT when the heat radiation absorbed by built structures in the urban area is released to the atmosphere. The AUHII\textsubscript{semi-urban} shows similar behaviour but less amplitude.

3.3.2 Surface Urban Heat Island (SUHI)

The LST in Mexico City is obtained from LANDSAT 8 data (Fig. 4). The high mountains to the south and the west of the city are mostly full of vegetation, and the temperatures detected are low (<10°C). The north and the east areas of the city have the warmest surface temperatures (Fig. 4).
In all images, the runway of the airport showed the hottest spot in the city with a surface temperature of around 45°C in February and March and around 50°C in April and May. The surface temperatures are in general higher during April and May. Fig. 4 was obtained with images taken on February 27, 2018, March 2, 2019, April 16, 2019, and May 18, 2018, because they were clear days with few clouds.

**Fig. 3.** (a) Monthly average AUHII and (b) Hourly average AUHII between urban (Tu) and rural (Tr) and urban (Tu) and semi-urban (Ts) stations during the dry season. All times are Local Times (LT).

**Fig. 4.** Land Surface Temperature LST retrieved from LANDSAT 8 images with few clouds (in yellow): February 27, 2018, March 02, 2019, April 16, 2018, and May 18, 2018. The Mexico City airport is in the circle line. Spatial resolution of 100 m.
### Table 2. Average SUHI intensity per region.

<table>
<thead>
<tr>
<th>Monthly</th>
<th>Rural (°C)</th>
<th>Semi-urban (°C)</th>
<th>Urban (°C)</th>
<th>Tu-Tr</th>
<th>Tu-Ts</th>
</tr>
</thead>
<tbody>
<tr>
<td>Feb</td>
<td>26.9</td>
<td>27.9</td>
<td>29.1</td>
<td>2.27</td>
<td>1.2</td>
</tr>
<tr>
<td>Mar</td>
<td>31.2</td>
<td>32.6</td>
<td>33.6</td>
<td>2.37</td>
<td>1.0</td>
</tr>
<tr>
<td>Apr</td>
<td>34.4</td>
<td>35.8</td>
<td>36.8</td>
<td>2.36</td>
<td>1.0</td>
</tr>
<tr>
<td>May</td>
<td>34.3</td>
<td>34.9</td>
<td>36.6</td>
<td>2.37</td>
<td>1.8</td>
</tr>
</tbody>
</table>

On average, the SUHI when subtracting urban and rural surface temperatures is 2.3°C and when subtracting urban and semi-urban surface temperatures is 1.2°C (Table 2). An average SUHI of 7.2°C has been reported by Chakraborty et al. (2019). The discrepancy in results is due to defining rural zones on top of mountains (with an average altitude of 3000 m above sea level). Whereas, in this study, rural areas were defined nearly at same average altitude of Mexico City.

### 3.4 The Urban Pollution Island

#### 3.4.1 UPI from air quality monitoring stations

The Urban Pollution Island is defined as the difference of pollution concentration in urban and rural areas due to different land cover and land use as well as local pollution sources (Ulpiani, 2021). Therefore, the Urban Pollution Island in Mexico City is measured by subtracting the PM concentration in rural and semi-urban areas from the concentration in urban areas measured by RAMA.

On average, PM$_{10}$ concentration is higher at rural stations than at urban stations for the period for February to May in GMC (Fig. 5(a)) because of bare soil favouring aeolian processes. Local sources in urban area include traffic and anthropogenic emissions. However, when comparing urban and semi-urban areas the PM$_{10}$ difference is positive, March has the lowest difference of around 2 µg m$^{-3}$ whereas the maximum value of 8 µg m$^{-3}$ is found in May. During the first 8 morning hours the UPI intensity of PM$_{10}$ is almost constant, then at 10:00 h LT the maximum difference of concentration (10 µg m$^{-3}$) is found, while a concentration of approximately zero is found at 18:00 h LT (Fig. 5(b)) when the concentrations are the same in urban and rural areas. The boundary layer height (~500 m) is smaller during the morning than during afternoon, thus, pollutants are trapped near the surface during the morning due and by traffic influx to downtown. Therefore, the lowest UPI values are found during the early morning and the evening. The latter due to a fully developed convective boundary layer that can reach 3000 m in height in April–May (García-Franco et al., 2018), which favors vertical dilution.

PM$_{2.5}$ concentrations are mostly higher in urban stations than in rural stations, therefore, the UPI is positive for most months (Fig. 5(c)). However, in April the concentration is slightly higher in the rural area than in the urban area. PM$_{2.5}$ sources are mostly due to human activities; therefore, it is expected that the urban area has a higher concentration, except when wildfires happen in rural areas. The UPI intensity is almost constant at around 3 µg m$^{-3}$. The difference between PM$_{2.5}$ concentration in urban and rural areas is maximum at 10:00 h LT with a value of 10 µg m$^{-3}$. However, during the first and last 8 hours of the day, PM$_{2.5}$ concentration is greater in rural areas than in urban areas (Fig. 5(d)) because one of the major PM$_{2.5}$ sources are vehicles. In Mexico City, there is heavy traffic from rural areas to the city center during the morning as the working day starts. During the evening, there is heavy traffic from the city center to rural and suburban areas when people go back home from work. The same behavior is found with PM$_{10}$ concentrations.

#### 3.4.2 Spatial distribution of AOD

The AOD is the indicator of air quality because it is related to both, PM$_{2.5}$ and PM$_{10}$ concentrations. Fig. 6 shows the spatial distribution of AOD and PM$_{2.5}$. The spatial distribution of AOD and PM$_{10}$ is shown in Fig. S4.

The highest concentrations of aerosol are found in the east of the city in the municipality of Chalco which is a low-rise building area with high population density and has a highway that connects Mexico City with Puebla with heavy duty traffic. In Chalco, there are many low-rise buildings or small houses next to each other and in some cases these houses are overcrowded.
Chalco has a major landfill (Tiradero Santa Catarina), an open-air sewage canal and an open-air gravel pit (Mina la Estancia) which contributes to aerosol emissions (Fig. 7(b)). Other areas with high AOD concentration are Iztapalapa (densely populated) and the northern area of Mexico City where there is a great industrial activity (Fig. 7(a)).

The open-air gravel pit has been identified as a major source of aerosol because advection process causes particles to travel to other parts of the city following the mean wind direction. In this case, the emission of aerosol flows southeasterly and reaches Granjas-Coapa and Iztapalapa (Fig. 7(b)). The same landfill has been identified as a PM source by Vega et al. (2001).

Furthermore, in April and May 2020, a major lockdown was enacted in GMC in order to stop the spread of the COVID-19 pandemic, as all non-essential activities were stopped, Chalco’s gravel pit stopped working and AOD concentration in Chalco decreased (Fig. S5). Therefore, the gravel pit has been identified as a major source of aerosol.

PM10 and PM2.5 spatial distributions are linearly related to AOD (Kong et al., 2016; Ranjan et al., 2021). Previous studies of wind direction and PM transport indicate that the main sources of PM10 in Mexico City are in Chalco and in the north near station ACO, the wind transports particulate matter from the south to the north through the eastern part of the city (Díaz-Nigenda et al., 2010).

3.5 Relation between UPI and UHI

The relation between UPI and UHI has been studied using data from the nighttime (00:00–07:59 h and 20:01–23:59 h LT). The UHI measured as the difference between temperatures in
urban and rural stations is defined as $UHI_{ur}$ and between urban and semi-urban stations is defined as $UHI_{us}$. Similar notation is used for the UPI. A good correlation between $UHI_{ur}$ and $UPI_{ur}$ and between $UHI_{ur}$ and $UPI_{us}$ has been found with PM$_{2.5}$ (Fig. 8).

No statistically significant correlations have been found between UPI defined with PM$_{10}$ concentrations and UHI during dry season at night. Also, during the autumn (Oct–Nov–Dec), significant correlations between UHI and UPI with PM$_{10}$ ($r = 0.53$ for $UHI_{ur}$, $UPI_{us}$) and UHI and UPI with PM$_{2.5}$ ($r = 0.47$ for $UHI_{ur}$, $UPI_{us}$) have been found (Fig. S6). During the autumn, greenery is still present from the rainy season, therefore, dust produced locally and moved by advection is minimal especially in rural areas where vegetation is abundant at this time of the year. Therefore, it can be concluded that, in the autumn, PM$_{10}$ is produced by local anthropogenic sources.

### 4 DISCUSSION AND CONCLUSION

The location of GMC as well as the unplanned growth of the city make it unique in terms of the UPI, UHI formation and PM distributions. From February to May, due to bare soil conditions, traffic induced abrasion and long-range transport of pollutants, AOD, PM$_{10}$ and PM$_{2.5}$ concentrations are higher than the rest of the year. Moreover, during the same period the UHI intensity is higher.

It has been found that PM$_{10}$ concentration in rural areas has a peak in the morning and another peak in the afternoon when the concentration is higher in rural areas than in urban areas due to the sources of PM$_{10}$ such as biomass burning being mostly in the suburbs. Furthermore, long-range transport of PM$_{10}$ follows the wind patterns from southeast to northeast of GMC and affects PM$_{10}$ concentrations (Díaz-Nigenda *et al.*, 2010; Fig. 8).

PM$_{2.5}$ concentration in urban areas is overall higher than in rural areas due to anthropogenic activities and traffic-induced abrasion. Moreover, an open-air gravel pit in Chalco is a major contributor to PM$_{2.5}$ in the east of the city and wind patterns cause long-range transport of PM$_{2.5}$

**Fig. 6.** (a–d) Spatial distribution of AOD and PM$_{2.5}$ in Mexico City. Obtained from MODIS and RAMA data, the monthly averages have been obtained with data from February 2017, March and April 2019 and May 2018. The size of red circles indicates PM$_{2.5}$ monthly average concentration obtained from RAMA data.
Fig. 7. (a) AOD distribution in March 2019, (b) detail and PM sources in Chalco, (c) wind rose for station CHO during day- and night-time using data from March 2019.

and cause the spatial distribution detected with MODIS data (Fig. 6). At night, the concentration in rural areas is greater than in urban areas (Fig. 5) because there is no traffic or other anthropogenic PM$_{2.5}$ sources so the concentration in urban areas decreases. Furthermore, the boundary layer is low during the night “trapping” pollutants near the surface. The interaction between UHI and UPI in GMC is stronger at night during the dry season because pollutants are concentrated near the surface trapping heat fluxes released to the atmosphere by the built environment and thus exacerbating the UHI effect (Cao et al., 2016).

Fig. 8. Relation between the UHI and UPI in Greater Mexico City during the dry season at night. _ur means defined between urban and rural stations whereas _us means defined between urban and semi-urban stations.
Also, the correlation between UPI PM$_{2.5}$ and UHI is positive at night (Fig. 8) and the UHI is higher at that time because the radiation absorbed during the day by built structures is released to the atmosphere. A limitation of this study is the lack of radiation data which could be used to quantify the contribution of aerosols to the UHI (Li et al., 2018).

The negative effect of PM$_{2.5}$ and temperature to the health are well known and documented. This study is relevant to understand that the increase in UPI intensity is related to an increase of the UHI intensity. In part due to anthropogenic sources of aerosols, particulate matter and heat. Other factors that need to be taken into account in future studies are the effect of wildfires and industrial activities further away of GMC. Poor air quality and high temperatures are harmful to Mexico City's inhabitants; therefore, actions to mitigate UPI and UHI are required.

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**SUPPLEMENTARY MATERIAL**

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**REFERENCES**


Feng, S., Gao, D., Liao,F., Zhou, F., Wang, X. (2016) The health effects of ambient PM$_{2.5}$ and


