Investigaciones Geográficas • Instituto de Geografía • UNAM
eISSN: 2448-7279 • DOI: https://doi.org/10.14350/rig.60855 • RESEARCH PAPERS
Issue 114 • August • 2024 • e60855
www.investigacionesgeograficas.unam.mx

Changing Climate in the Metropolitan Zone of Xalapa, Veracruz: Natural and Anthropic Factors

Clima cambiante en la Zona Metropolitana de Xalapa, Veracruz: factores naturales y antrópicos

Nuria Vargas* and Mary Frances Rodríguez Van Gort**

Received: 29/01/2024. Accepted: 25/3/2024. Published: 15/05/2024.

Abstract. Urbanization induces climate changes such as the so-called Urban Heat Island (UHI). The Xalapa Metropolitan Zone (XMZ), Veracruz, has experienced accelerated urban growth in the past three decades, producing a warming trend. However, the strong climatic influence of the Gulf of Mexico slope also acts as a climate modulator in the region, through forms of variability in decadal periods, such as the Atlantic Multidecadal Oscillation (AMO). The present study establishes a relationship between the maximum surface temperature of the XMZ, the AMO index, and urbanization, as natural and anthropogenic forcing, respectively. Averages of data from weather stations, satellite and reanalysis data were used. Through time series plots and spectral analysis, it was possible to determine the relationship between the variables of interest. The results indicate that the areas of the city where there has been a drastic change in land use, for example, from forest to urban land, have experienced a warming of about 2ºC in the last two decades, despite a positive phase of the AMO index, in which it would be expected that temperatures would not increase in this way. On the other hand, in the part of the XMZ where the urban development model preserves a large part of trees and vegetation, temperatures change mostly in relation to the natural forcing, i.e., the AMO index.

Thus, the city of Xalapa and its metropolitan area are an example of the influence of natural climate variability factors (AMO), as well as anthropic factors (urbanization) that generate local climate change on a time scale of decades, so that the most complete analysis of very long period variation in climate must take into account the natural forcing on these time scales.

Keywords: climate variability, Atlantic Multidecadal Oscillation, land-use change, urbanization, maximum temperatures, climate variability, land-use change, urbanization, maximum temperatures.

Resumen. La urbanización induce cambios en el clima como la llamada Isla de Calor Urbana (UHI). La Zona Metropolitana de Xalapa (XMZ), Veracruz, ha experimentado un crecimiento urbano acelerado en las últimas tres décadas, lo que produce una tendencia al calentamiento. Sin embargo, la fuerte influencia climática de la vertiente del Golfo de México, también actúa como modulador del clima en la región, por formas de variabilidad en períodos decadales, como la Oscilación Multidecadal del Atlántico (AMO por sus siglas en inglés). En el presente estudio se establece una relación entre la temperatura máxima de superficie de la XMZ, el índice AMO, and la urbanización, como forzantes de origen natural and antrópico, respectivamente. Se usaron promedios de datos de estaciones climáticas, datos de satélite and de reanálisis. A través de gráficas en series de tiempo and un análisis espectral, fue posible determinar la relación

---

* Facultad de Filosofía y Letras. Universidad Nacional Autónoma de México (UNAM). Circuito Interior s/n, C.U., Coyoacán, 04510, Ciudad de México, México. ORCID: https://orcid.org/0000-0002-6369-691X. Email: nunube@gmail.com
** Facultad de Filosofía y Letras. Universidad Nacional Autónoma de México (UNAM). Circuito Interior s/n, C.U., Coyoacán, 04510, Ciudad de México, México ORCID: https://orcid.org/0009-0003-3996-2282. francesrv@gmail.com

existente entre las variables de interés. Los resultados indican que las zonas de la ciudad donde ocurre un cambio de uso del suelo drástico, como por ejemplo al pasar de bosque a suelo urbano, se ha experimentado un calentamiento del orden de 2ºC, en las últimas dos décadas, a pesar de presentarse una fase positiva del índice AMO, en la que se esperaría que las temperaturas no incrementaran de esa manera. Por otro lado, en la parte de la XMZ donde el modelo de desarrollo urbano conserva gran parte de arbolado and vegetación, las temperaturas cambian mayormente en relación con el forzante natural, es decir, por el índice AMO.

Así, la ciudad de Xalapa and su área metropolitana son un ejemplo de la influencia de factores de variabilidad natural del clima (AMO), así como de factores antrópicos (urbanización) que generan un cambio climático local en escala temporal de décadas, por lo que el análisis más completo de la variación de muy largo periodo en el clima debe tomar en cuenta los forzantes naturales en estas escalas temporales.

Palabras clave: variabilidad climática, Oscilación Multidecadal del Atlántico, cambios del uso del suelo, urbanización, temperaturas máximas.

INTRODUCTION

For several years now, there has been growing concern about the impacts of climate change on society (IPCC, 2007). Adaptation projects are generally based on the expected or projected climate that commonly corresponds to temperatures higher than current ones (IPCC, 2000) . However, the climate for the coming decades will depend on several factors that are frequently not considered in climate change scenarios, which significantly influence the climate and lead to climate anomalies, mainly at regional or local scales, such as cities. Thus, global climate change must be compounded by the effect of climate fluctuation processes by very low-frequency natural factors or local effects such as the urban heat island (UHI).

The issue of climate change in urban environments has been studied for more than a century (Howard, 1818; Oke *et al.*, 2017). The formation of UHI in medium-sized and large cities is identified by analyzing the contrast between the temperature of the urban area compared to its rural periphery (Oke, 1967; Manoli *et al.*, 2019). In Mexico, since the 1970s, the number of medium-sized cities has increased, and there are currently more than 70 metropolitan areas in the country, with a population of around or more than one million inhabitants. This trend towards a mostly urban population has led to the formation of UHIs that, in some cases, can pose a health risk to local inhabitants. UHIs were initially documented in various parts of Mexico by Jáuregui (Jáuregui, 1993, 2009); his studies are still the basis for current analyses of this issue. Other authors are currently investigating this phenomenon and the impacts associated with UHIs (Tejeda & Acevedo, 1990; Vargas & Magaña, 2020; García-Cueto *et al.*, 2007).

In Mexico, UHIs have been described based on the trend of maximum temperature in recent decades (Jáuregui, 1993, 2009). In some cases, the effect of the UHI on precipitation in cities has also been described as part of climate changes that induce changes in land use (Jáuregui & Romales, 1996). However, there are variations over decades in climate, for example, in temperature or precipitation, related to very low-frequency natural climate forcings (e.g., Azhar *et al.*, 2020). Particularly, the Atlantic Multidecadal Oscillation (AMO) is a major natural climate forcing in the tropics (Azuz-Adeath *et al.*, 2019; Jae-Heung & Li, 2018), whose signals (climatic fluctuations) explain conditions such as meteorological droughts in Mexico (Méndez & Magaña, 2010). Thus, very low-frequency variations in the regional climate may be due to anthropogenic or natural forcing factors. In some cases, the magnitude of the UHI may exceed the forcing effect of the AMO; this facilitates projecting the evolution of the climate in the coming decades, mainly considering urban growth projections. In this way, the effect of global warming must be added to the effects of the UHI and AMO on forecasting the climate on decades-long scales.

The Xalapa Metropolitan Zone (XMZ), located in central Veracruz (Figure 1), has experienced rapid demographic and territorial growth since the early 2000s, from a population of 591,053 inhabitants to 789,157 inhabitants in 2020 (Table 1). Its size was 44,400 hectares in 2000, and it expanded to 109,000 hectares in 2020, with a population density that increased from 13 inhabitants/ha to

7 inhabitants/ha. This implies a greater occupation of areas with a low population density that requires greater resources in terms of land, energy, and services. An urban growth model of this type generates more pollution and is unsustainable; therefore, an optimal population density has been established, ranging from 120 inhabitants/ha to 350 inhabitants/ha (Higueras, 2009). Thus, the population of the XMZ is approaching the threshold of one million inhabitants, for which Tejeda, Luyando, and Jáuregui (2011) propose a formula to estimate potential temperature rises due to the effect of the UHI. According to Tejeda (Tejeda *et al.,* 2011), the temperature rise resulting from the UHI could be up to 1 ºC for a population of around 600,000 inhabitants. This approach assumes that urban development follows the traditional vegetation or forest conversion pattern into urban landscapes. If the population in the XMZ continues approaching one million inhabitants, the estimate indicates that the urban-rural thermal contrast of the UHI could be approximately 2 ºC. However, such temperature increases will depend on the urbanization model to be followed. Some proposals show that conserving vegetation or metropolitan water bodies can mitigate the intensity of the UHI (Schwaab *et al.*, 2021; Gunawardena *et al.*, 2017). Therefore, documenting climate changes in cities requires considering the urban growth model followed or projected.

On the other hand, projecting the climate of a place, for example, including decadal periods, requires including large-scale and very long-term natural processes reflected in the local climate, such as the AMO, whose effect on Xalapa and its surroundings should be determined and included in any projection. Furthermore, future global warming scenarios for the coming decades will determine the climate of Xalapa. Therefore, mitigation and adaptation actions must consider potential climate scenarios.

This paper reports the analysis of very-low-frequency climatic variations (decades) in an urban area such as the XMZ, which shows the role played by the urban growth model, with or without vegetation conservation, as well as the effect exerted by fluctuations in the local climate by very-low-frequency phenomena such as the AMO, and the effect of the global warming trend. The work is divided as follows: the first section outlines a brief introduction to the issue and the objective of the study. The second section describes the data sources used for the analysis and the methodology followed. The results and their interpretation are included in the third section, and the fourth section states the conclusions drawn from the study.

DATA AND METHODOLOGY

As most medium-sized cities of Mexico, Xalapa has incorporated neighboring municipalities into its urban area to become a Metropolitan Zone (Figure 1). This rapid urbanization has generated a UHI that can be identified through Land Surface Temperature (LST) satellite images available at Climate Engine, NASA-MODIS, LST (https://www.climateengine.org). The urban growth of the study area was documented through satellite images and using information from basic urban geostatistical areas (INEGI, 2000, 2010, and 2020) to learn about the urban expansion that has taken place in Xalapa and its metropolitan zone. In addition, Sentinel satellite images were available to delineate the world's cities and towns for 1975, 1990, 2000, and 2020 (Pesaresi and Politis, 2023).

Table 1. Inhabitants, occupation area, and population density of the Xalapa Metropolitan Zone, Veracruz.

XMZ	1990	2000	2010	2020
Number of inhabitants	461 108	591 053	711 139	789 157
Surface area (km²)		444	867	1090
Population density (inh./ha)		13.3	8.2	7.2

Source: INEGI-CONAPO (2004, 2020), SEDATU (2015).

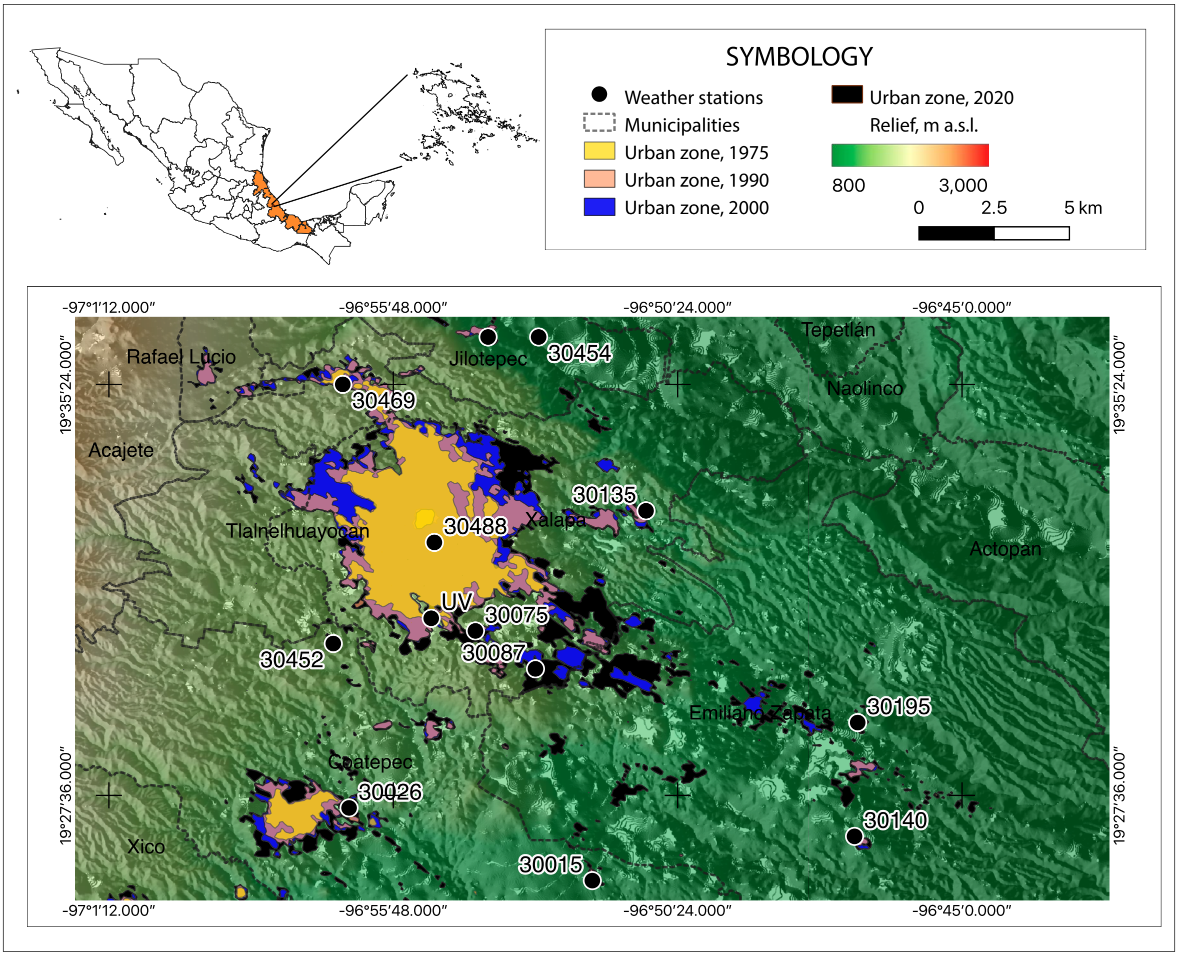

Figure 1. Urbanized area of the XMZ in 1975, 1990, 2000, and 2020; the figure shows the orography and location of the weather stations used in this study. Source: Authors' own elaboration with data from INEGI, GHS (2022), CONAGUA, and Universidad Veracruzana.

Daily air temperature data around the XMZ were obtained for an average period of 1960 to 2020 from the network of climatological stations of the National Water Commission (CONAGUA, 2023) and, in recent years, from the station of the *Universidad Veracruzana* (UV) (Figure 1). The climate trends in the Xalapa region and peripheral areas were diagnosed using daily data from twelve weather stations of the CONAGUA observation network. The corresponding time series cover different periods and, despite existing information gaps, jointly support the analysis of local climate variations and trends (Table 2).

Very low-frequency climatic variations in the XMZ can be related to AMO conditions, as suggested for other regions of the world (Azhar *et. al.*, 2020). AMO index data was obtained from the National Oceanic and Atmospheric Administration (NOAA) (2023) and compared with average data from XMZ stations. In addition, a spectral analysis was used to corroborate the interdecadal relationships between the AMO index and the maximum temperatures in the XMZ. Furthermore, we used global temperature data from the National Center for Environmental Information (NCEI) and NOAA, which show the global warming process. For the

Table 2. Weather stations used for the study, data periods, data coverage percentages, and station location.

Station ID	Data period	Data Coverage Percentage	Coordinates
30075	1951–2018	80%	-96.9040, 19.5120N
30087	1953–2012	73%	-96.8850, 19.5000N
30015	1964–1989	44%	-96.8670, 19.4330N
30452	1984–2018	100%	-96.9490, 19.5080N
30026	1961–2018	76%	-96.9440, 19.4560N
30195	1964–2009	100%	-96.7830, 19.4830N
30140	1969–2018	100%	-96.7840, 19.4470N
30267	1974–2018	95%	-96.9000, 19.6050N
30469	2004–2018	95%	-96.9460, 19.5900N
30454	1995–2018	96%	-96.8840, 19.6050N
30135	2005–2018	96%	-96.8500, 19.5500
30488	2011–2015	80%	-96.9170, 19.5400
UV	2011–2022	100%	-96.9182, 19.5163

present analysis, only temperatures in the Gulf of Mexico were considered, which reflect the warming process in the region as a sign of the global climate warming process.

Time series analysis estimates the extent to which each climate forcing contributes to the climate variations and trends observed in the MXZ between 1960 and 2018; we compared the contribution of the following factors: i) urbanization, ii) the AMO index, and iii) the global warming process. We also compared the warming patterns with the greenness level related to the Enhanced Vegetation Index (EVI), which shows how urban expansion reduces the existing vegetation. The EVI data for the period 2000–2022 are available at https://www.climateengine.org

RESULTS

Estimates of Interdecadal Temperature Changes

Until 1990, the Xalapa Metropolitan Zone (XMZ) was configured as a compact nucleus in the municipality of the same name. However, since 1990, urban expansion has incorporated neighboring municipalities in a fragmented occupation of the territory with a great impact on vegetation loss (Figure 1). As a result, the XMZ now encompasses six municipalities located on the slope of the Sierra Madre Oriental with a marked orographic gradient, which determines low temperatures at higher altitudes towards the east while the temperature increases significantly toward the west.

The urban expansion process has led to the conversion of forests and agricultural areas to infrastructure with buildings, houses, streets, and other architectural elements where concrete, asphalt, and glass dominate; these materials alter the local radiative balance and have led to the formation of an urban heat island (UHI) (Oke, 2017). It is worth mentioning that Mexican cities typically follow this growth model today.

According to data from the ERA5 meteorological reanalysis (available since 1979), mean annual maximum and minimum temperatures tended to increase towards the end of 1990 (Figure 2), followed by a stable period, increasing significantly again after 2015. However, these trends reflect variations over a forty-year period only (1979–2020) and average relatively large areas compared to the size of the urban area. Therefore, to analyze the temperature change rates, it is also necessary to consider data from weather stations located at

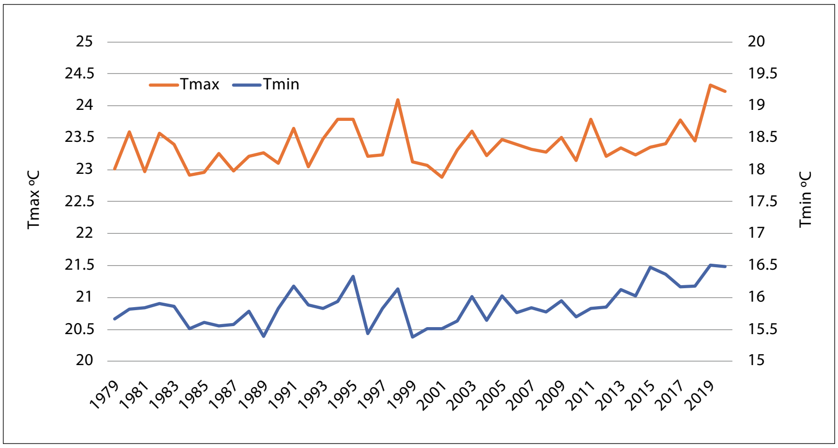

Figure 2. Maximum and minimum temperatures, annual average in the domain corresponding to urbanized areas of the Xalapa Metropolitan Zone between 1979 and 2020 with reanalysis data. Source: ERA 5Ag.

various points in the XMZ or use graphs of land temperature captured by satellites as a proxy for air temperature.

Although the frequency of land temperature estimates is irregular, at about a week, a smoothed version allows for identifying that the temperature increases between 1990 and the year 2000 and then decreases towards the end of 2020. Such an estimate of very low-frequency variations in minimum and maximum temperatures shows a slightly downward trend in temperature in the past decade (2010–2020). Although the analysis contemplates the urbanized and undeveloped part of the XMZ and its surroundings, some factors induce not only warming but also a slight recent cooling.

Another approach to analyzing the variations in interdecadal temperature in the XMZ and its surroundings is through land surface temperature averaged per decade (Figure 3). For example, data from 1993 to 2022 reveal changes over ten-year periods. Thus, between 1993 and 2002, the prevailing temperature was 24 ºC and, to a lesser extent,

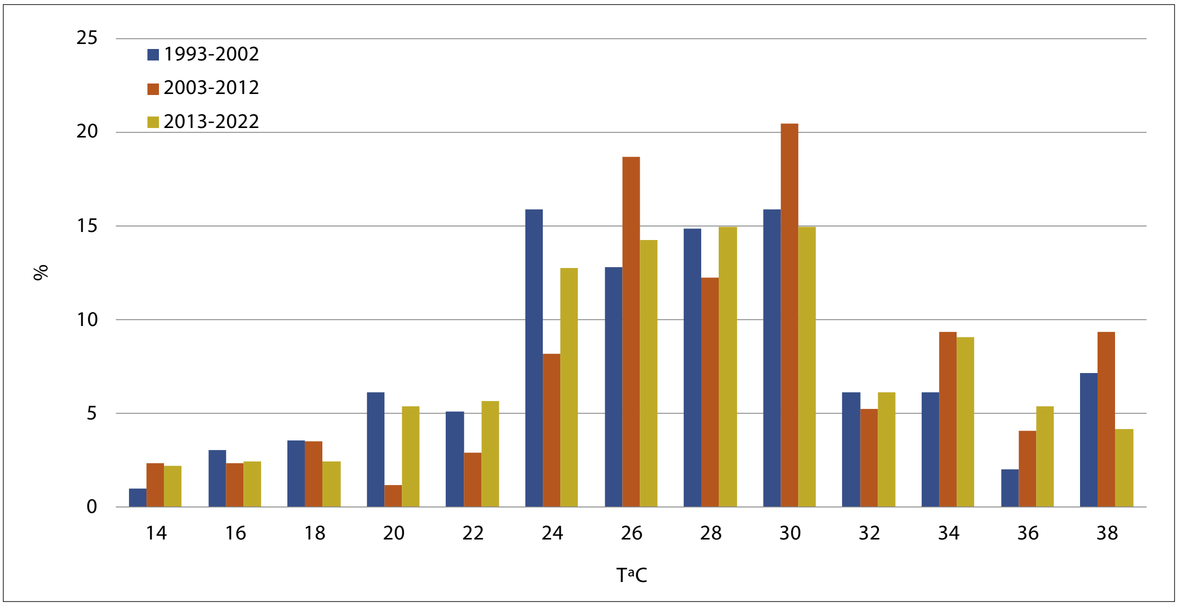

Figure 3. Frequency diagram of land surface temperature by periods, a) 1993-2002 (blue bars), b) 2003-2012 (orange bars) and c) 2013-2022 (yellow bars).

30 ºC, while between 2003 and 2012, the most frequent temperature was around 30 ºC. Finally, for the period 2013–2022, the most frequent temperatures ranged between 28 ºC and 30 ºC, which were lower than in the previous decade, indicating a slight decrease in temperature.

When observing the spatial distribution of surface temperature, a slight decrease in surface temperature is observed in the period 2010-2020 (Fig. 4b) versus the period 2000-2010 (Fig, 4a). In the XMZ and its surroundings, the areas with the highest land temperature are the urbanized zone and the agricultural areas or pastures in the east, which are at the lowest altitudes (<1000 meters above sea level), frequently consisting of bare soil susceptible to intense heating. On the other hand, high mountainous areas are located to the west of the domain, with forests and vegetation that maintain a low land temperature. In the urban zone, the highest temperatures correspond to parks, lakes, and state-protected and peri-urban areas. The pattern of land temperature in and around the XMZ allows for a clear identification of the UHI within the urban area. For the second period of analysis, generalized cooling is observed. This suggests a recurrent, very low-frequency climate regulation process.

Data from meteorological stations in the domain of interest allow for the analysis of the evolution of the maximum temperature in the XMZ since 1950. The monthly mean values of maximum temperature recorded in urban stations reveal very low-frequency oscillations (interdecadal) in this domain. Despite missing data in certain periods, the information is sufficient to establish the behavior of the climate during decadal periods. Between 1950 and 1970, the mean annual maximum temperature ranged from 19 °C to 22 °C. In the 1970s and mid-1990s, temperatures ranged from 21 °C to 24 °C. Since 2000, maximum temperatures at some stations have dropped to ranges between 17 °C and 20 °C, while other stations have remained between 20 °C and 23 °C (Figure 5). This oscillation in the maximum temperature suggests a climatic regulation effect given by a forcing with similar temporal characteristics. There is an inverse relationship between the AMO index and maximum temperatures in several XMZ stations. When the AMO index is positive (negative), maximum temperatures tend to drop (increase), possibly due to cloudy sky conditions that reduce direct radiation. Under the opposite conditions, with a negative AMO index, atmospheric conditions tend to be drier, which leads to fewer clouds and, consequently, the radiation reaches the land surface directly, producing a warming effect. However, the relationship between these variables became less marked after 1990, when the drop of maximum temperatures was weaker in urban stations than in stations that maintain a rural character. For the past two decades, with the positive AMO phase (AMO (+)), the dense urbanization context has caused temperatures in urban areas to remain high, contrary to the previous period of an AMO (+) phase. In other words, between 1948 and 1963, stations in the urban area remained with maximum temperatures between 21 °C and 23 ºC, while recent values range between 23 °C and 25 ºC. Therefore, urbanization appears to have influenced the temperature rise of approximately 2 ºC, as Tejeda *et al.* (2011) propose. In contrast, stations 30452, 30454, and 30135, located in an environment with more vegetation, show lower maximum temperatures, following the maximum temperature pattern of the 1950s-1960s. A special case is station 30452, located in an area known as Briones, which has maintained the forest around it.

Additionally, a spectral analysis identified the relationships between the AMO index and maximum temperatures in the study area. The monthly maximum temperature data available from the domain were averaged for the entire period of interest. For the AMO and the maximum temperature, the highest power corresponds to the annual cycle. However, as the present analysis addresses only the very low frequencies (long periods), the power is only shown for periods longer than one year, i.e., interannual and multidecadal. The power spectrum was multiplied by frequency to highlight "spectral peaks" of shorter periods (Figure 6). The spectrum shows that the AMO index has a great variance, mainly in periods of around 30 years (362 months) and interannual periods between 2 and 3.6 years (24 and 45.3 months, respectively).

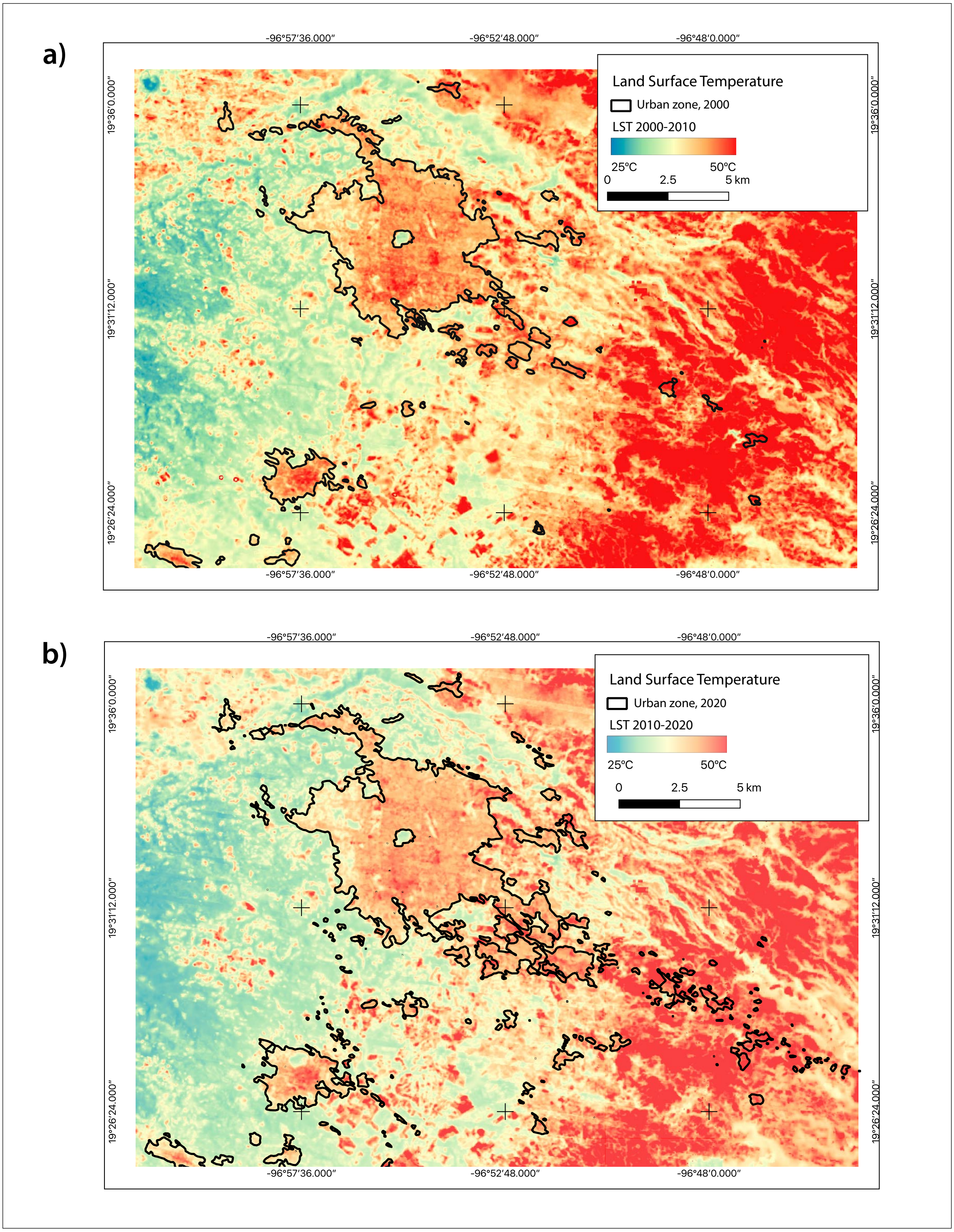

Figure 4. Mean annual land surface temperature for the periods a) 2010–2020 and b) 2010–2020. Source: Climate Engine (2023).

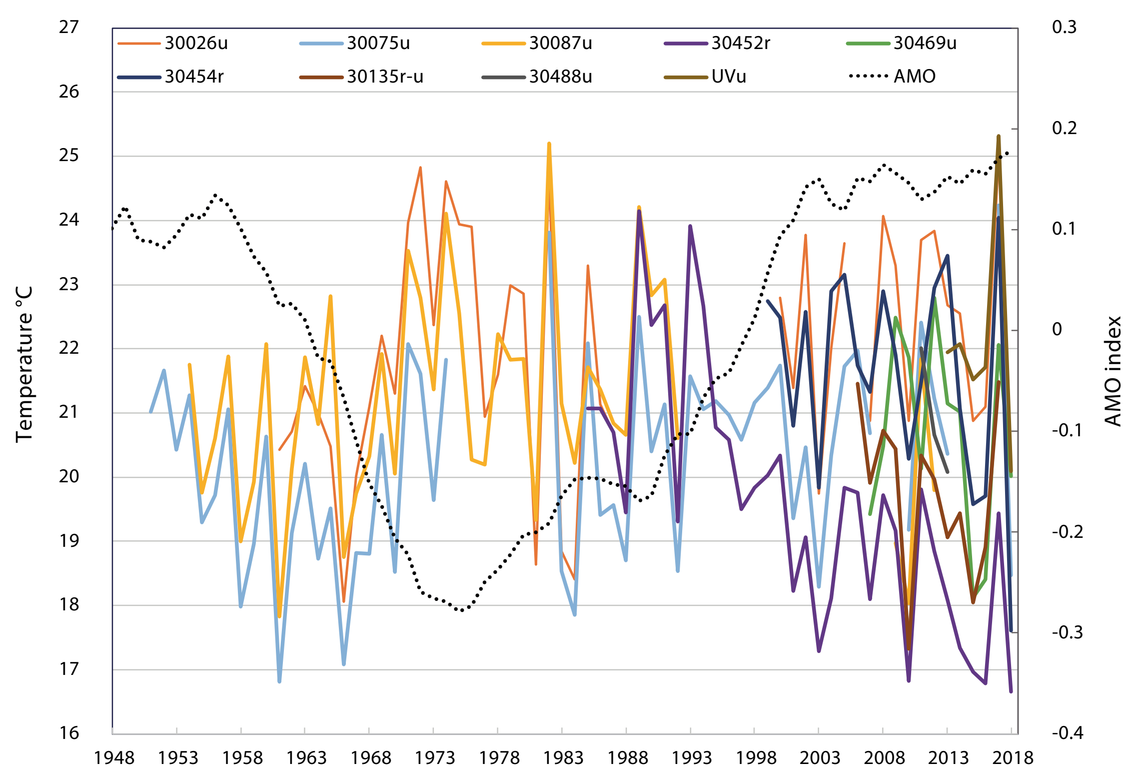

Figure 5. Mean annual maximum temperatures for rural (r) and urban (u) stations within the XMZ. The black dotted line indicates the AMO index.

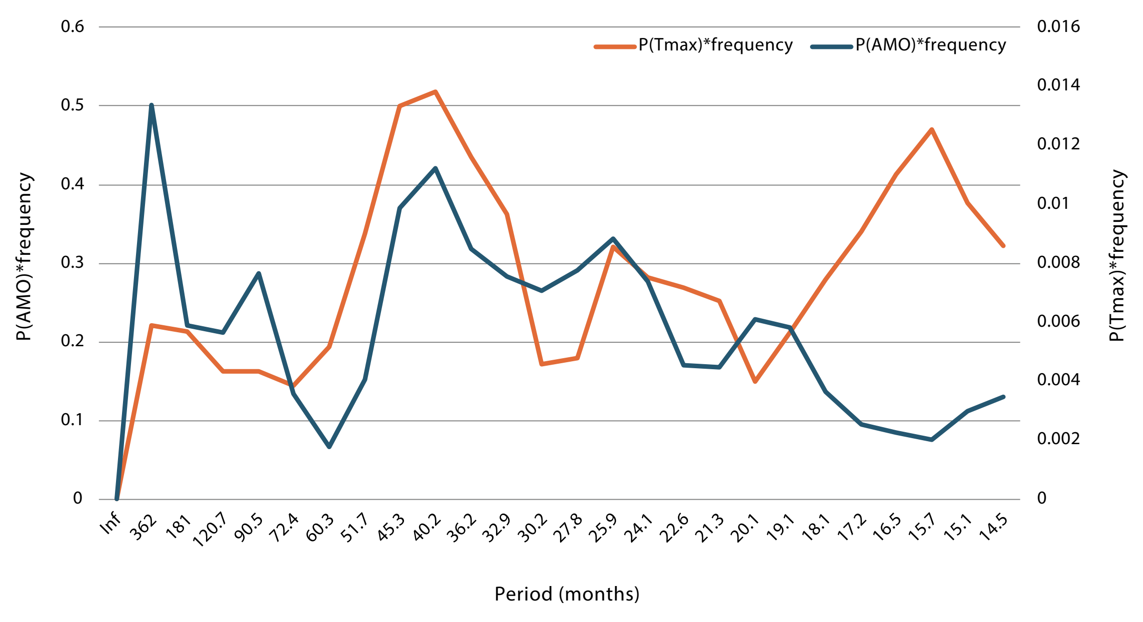

Figure 6. Power spectrum multiplied by the frequency for the AMO (blue line) and the maximum temperature in the XMZ (orange line), obtained with monthly mean data of the AMO index and the maximum temperature for the period 1951–2020.

In the low frequencies, the maximum temperature in the XMZ also exhibits a spectral peak around 30 years, as well as a high variability between 2 and 3.6 years, as observed with the AMO index.

When analyzing the squared coherence and phase difference between the AMO index and the maximum temperature in the XMZ, the most significant values (greater than 0.25) correspond to periods of more than 30 years (Figure 7). Although there are squared coherence maxima for periods of 21.3 and 17.2 months, the corresponding AMO power is very low, so its statistical significance is low. The phase difference in the 30-year period is around 180°, which means that the series in these periods are out of phase, as observed in Figure 5, corresponding to the time series of the AMO index and maximum temperature. Coherence increases slightly at a very low frequency (period of more than 30 years) if the mean number of stations only considers the Briones station (30452) in the period 2000–2020.

The results of the spectral analysis for low-frequency variations show that, naturally, the very-low-frequency variations of the AMO are negatively correlated with maximum temperature variations in Xalapa. However, in recent decades, the effect of the UHI appears to disrupt this relationship by maintaining a trend of urban warming.

Importance of Land Use as a Local Climate Regulator

The Briones area (station 30452) stands out for remaining with vegetation; therefore, its maximum temperature behavior is as expected. Maximum temperature records from 1984 onward indicate a trend to decrease after the year 2000, consistent with the regulation exerted by the AMO for positive-phase periods in areas with natural vegetation (Figure 5). The urbanization model of Briones within the XMZ corresponds to a landscape of residential households amidst a dense wooded area that behaves as a natural vegetation land-use area. In this way, the temperature at this station contrasts with the XMZ urbanized area, where the maximum temperature is at least 2 °C higher. The regional average temperature in the Gulf of Mexico also rises by just over 1 °C without affecting the temperature trend in Briones (Figure 8). This relationship suggests that the temperature regulation of cloudiness and the incoming solar radiation, determined by dynamic processes such as the passage of *Nortes* (winter storms) or easterly waves, are the drivers in the Gulf of Mexico slope rather than the temperature in the Gulf of Mexico as such, particularly in areas covered by vegetation.

The urbanized area of Xalapa expanded from 10.22 km^2 in 1950 to 124.4 km^2 by 2020

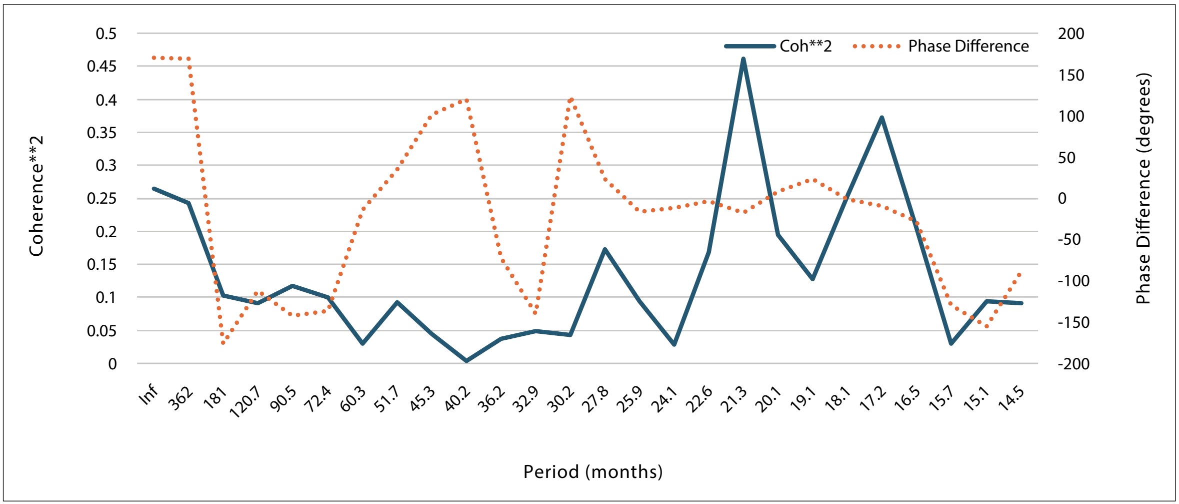

Figure 7. Squared coherence (blue line) and phase difference (orange line) between the series of monthly AMO values and maximum temperatures in the XMZ for the period 1951–2020.

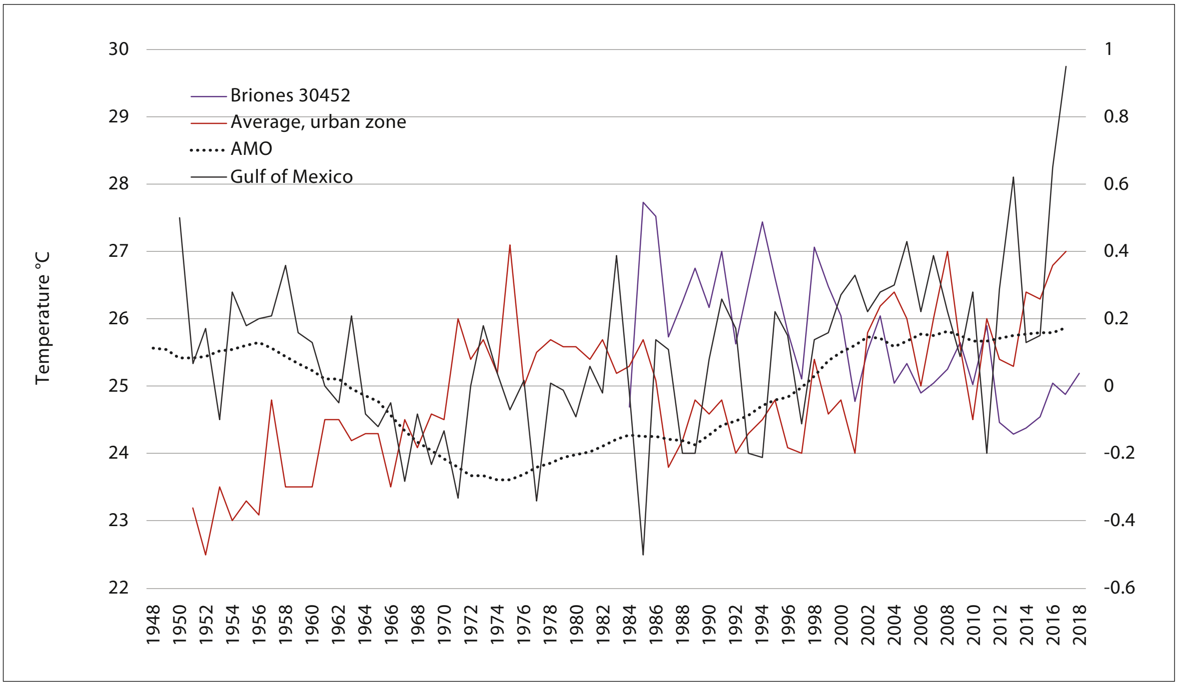

Figure 8. Average maximum temperature for the urban area, Briones station 30452 (rural area), AMO index, and temperature anomalies in the Gulf of Mexico (proxy for global warming).

(SIEGVER, 2021). The greatest urban growth or expansion occurred in the 1990s, when ejido and communal land could be commercialized (Benitez, 2011), coinciding with the period when much of the XMZ began to undergo a warming process. The urban area expanded at the expense of a loss of vegetation, which is evident through the Enhanced Vegetation Index (EVI).

In the period 2000–2020, at the end of the summer rainy season, when the EVI reached peak values, relative minima can be detected in zones where urbanization is denser, such as the center of Xalapa city (Figure 9). In contrast, in peripheral urban areas, EVI values are relatively high (greater than 0.5), reflecting the relative conservation of vegetation. The pattern of low EVI values in the urban area coincides with higher land temperatures in Figure 4a.

The urbanization growth trend (Figure 1) occurs mainly in the east and southeast of the XMZ. In this area, vegetation loss is reflected in a negative trend in the EVI (Figure 10), a flat land previously dedicated primarily to agriculture and livestock raising. Vegetation loss associated with urban growth has resulted in rises in land surface temperature that generally lead to the formation of the UHI.

Thus, the climate forcing associated with changes in land use plays a central role in the long-term variations and trends of the climate in the XMZ.

To estimate the impact of vegetation loss with the EVI, we also analyzed the trend of changes in land temperature between 2000 and 2020 (Figure 11). The areas that experienced the greatest warming are those that experienced the worst vegetation loss. Thus, urbanization can induce maximum temperature rises of more than 2 °C in two decades (2000–2020), which makes land use changes the main climate forcings in the XMZ, on top of the trends of anthropic global warming or the natural forcing associated with the AMO.

DISCUSSION AND CONCLUSIONS

The loss of ecosystem services provided by vegetation removes a source of significant thermal

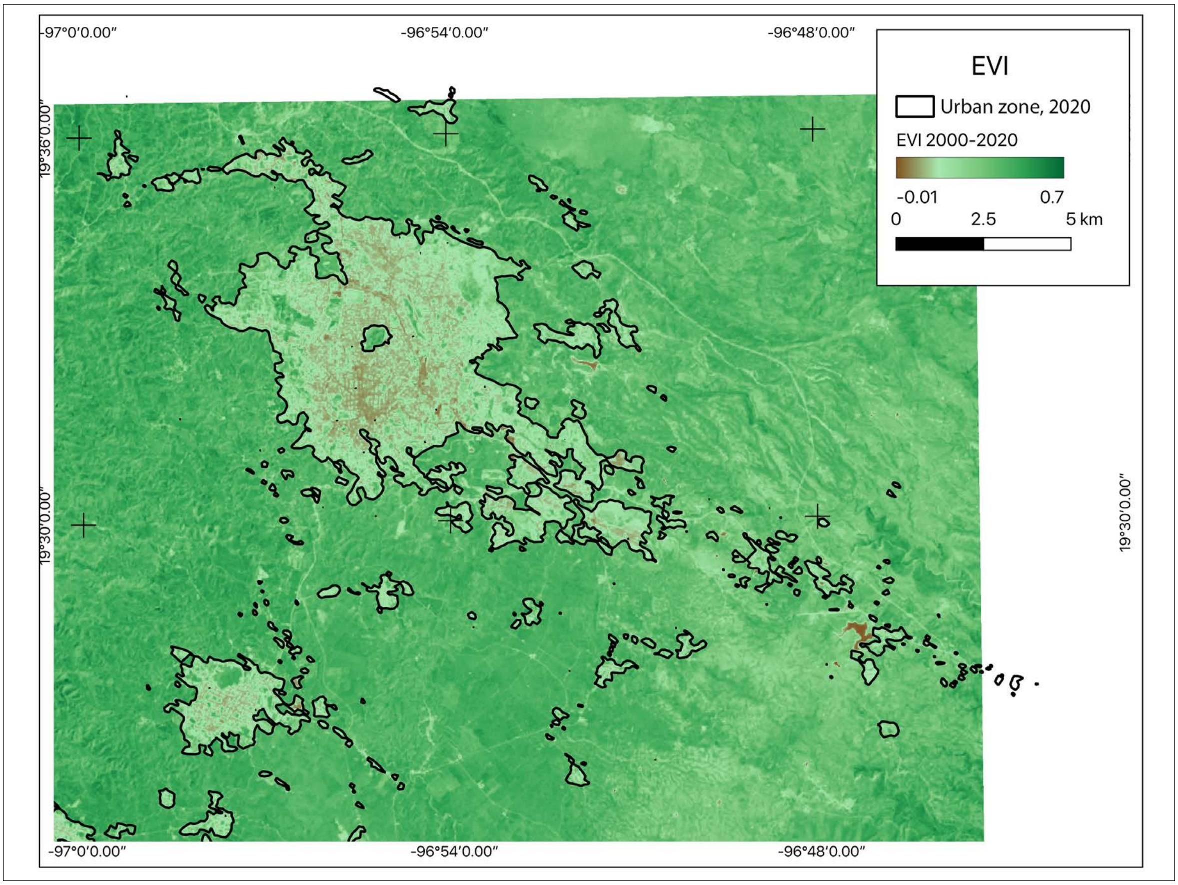

Figure 9. Average Enhanced Vegetation Index (EVI) for the period 2000–2020. Source: Climate Engine (2023).

regulation. Trees contribute to lowering the surface temperature generated by high solar radiation levels, and the moisture of a vegetated soil that uses this energy for evapotranspiration alters the climate in urbanized areas. The growth model of cities in Mexico usually involves the removal of trees and vegetation. This leads to rising temperatures despite the influence of natural forcings, such as the AMO, which would tend to cool down the climate, as in the XMZ.

The present analysis identified a relationship between the natural variability of the Atlantic climate, such as the AMO, and the climate in a part of the Gulf of Mexico slope, the XMZ. However, this relationship wanes because the forcing due to land use change has gained a growing importance in recent decades. The relationship of natural climate variability regulated by the AMO appears to remain only in some urbanized areas that maintain a high vegetation coverage, such as the Briones neighborhood.

The way in which the Xalapa Metropolitan Area has grown has had consequences on maximum temperatures. Although most of these consequences have followed a positive trend, it is important to recognize that not all areas have followed the same growth model, making it possible to visualize that there are ways that allow for buffering high temperatures and thus avoid impacts on the population, as in the case of Briones.

On a separate topic, although the city and its urban area are located on a heterogeneous land characterized by steep slopes and plains and differences in altitude between 1000 and 1600 meters

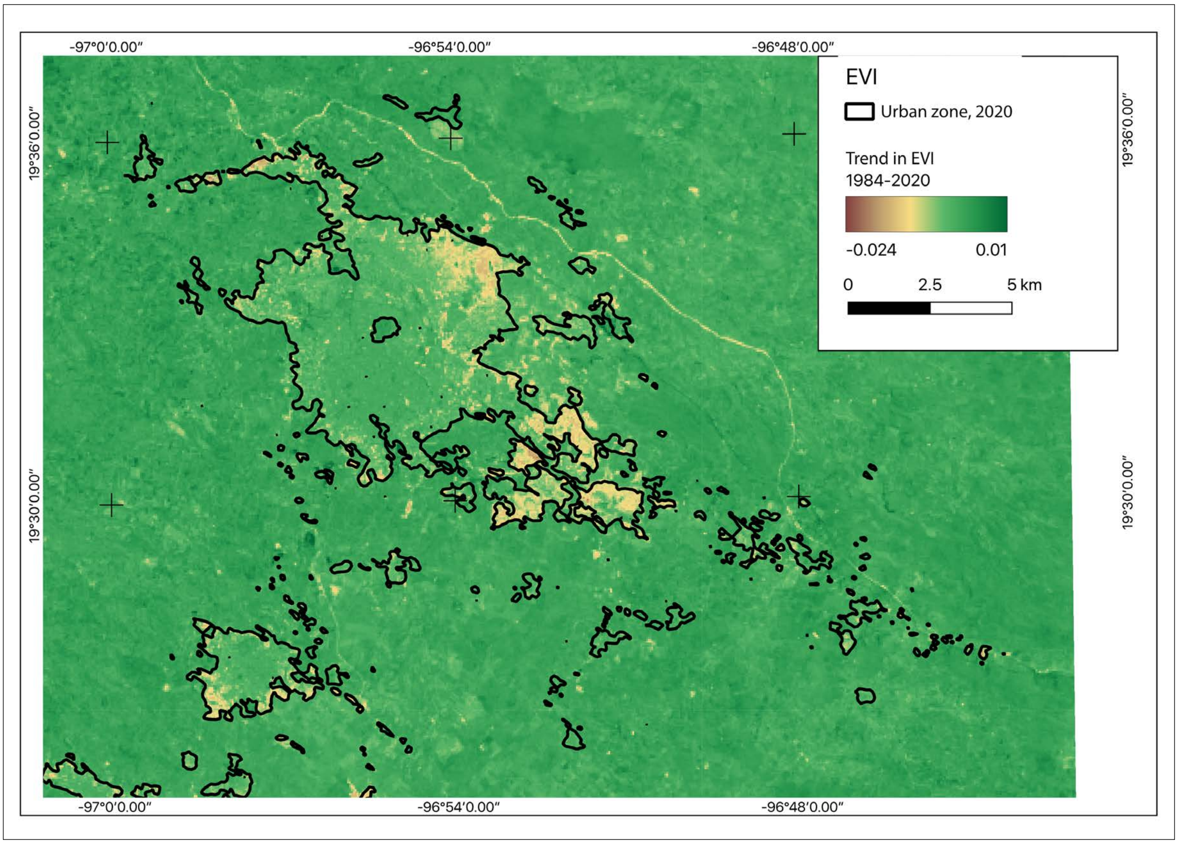

Figure 10. Trend of the Enhanced Vegetation Index (EVI) for the period 1984–2020. Source: Climate Engine (2023).

above sea level, the area as a whole has undergone a warming trend induced by urbanization, and, in the past, by the negative phase of the Atlantic Multidecadal Oscillation. In the coming years, during which the factors that produce warming in the area may act together, the potential effects will be worrying. In this regard, one death was recorded this year on the outskirts of the city due to a heat wave (Vanguardia de Veracruz, 2023). This can be a wake-up call for government authorities and civil society to put in place prevention measures to face a scenario in which extreme temperatures are becoming more frequent.

The present study only addressed the maximum temperatures influenced by the AMO; however, changes in precipitation, which can also be affected by urbanization, should also be investigated (Jáuregui and Romales, 1996).

CONCLUSIONS

The Xalapa Metropolitan Zone has experienced changes in maximum temperature over the past 60 years, evolving from an average of 23.5 ºC before 1960 to 26 ºC between 2010 and 2018.

During the negative AMO phase, maximum temperatures reached 25.5 ºC, largely influenced by such natural climate variability since this phase coincided with a sparse and widespread XMZ.

The analyses that explain temperature changes are important today to generate proposals to reduce such temperatures in urban areas because of the high exposure of populations that may be affected by high temperatures that may cause health issues and influence mortality.

The urban growth of the XMZ should be planned, since a trend of rising temperatures can

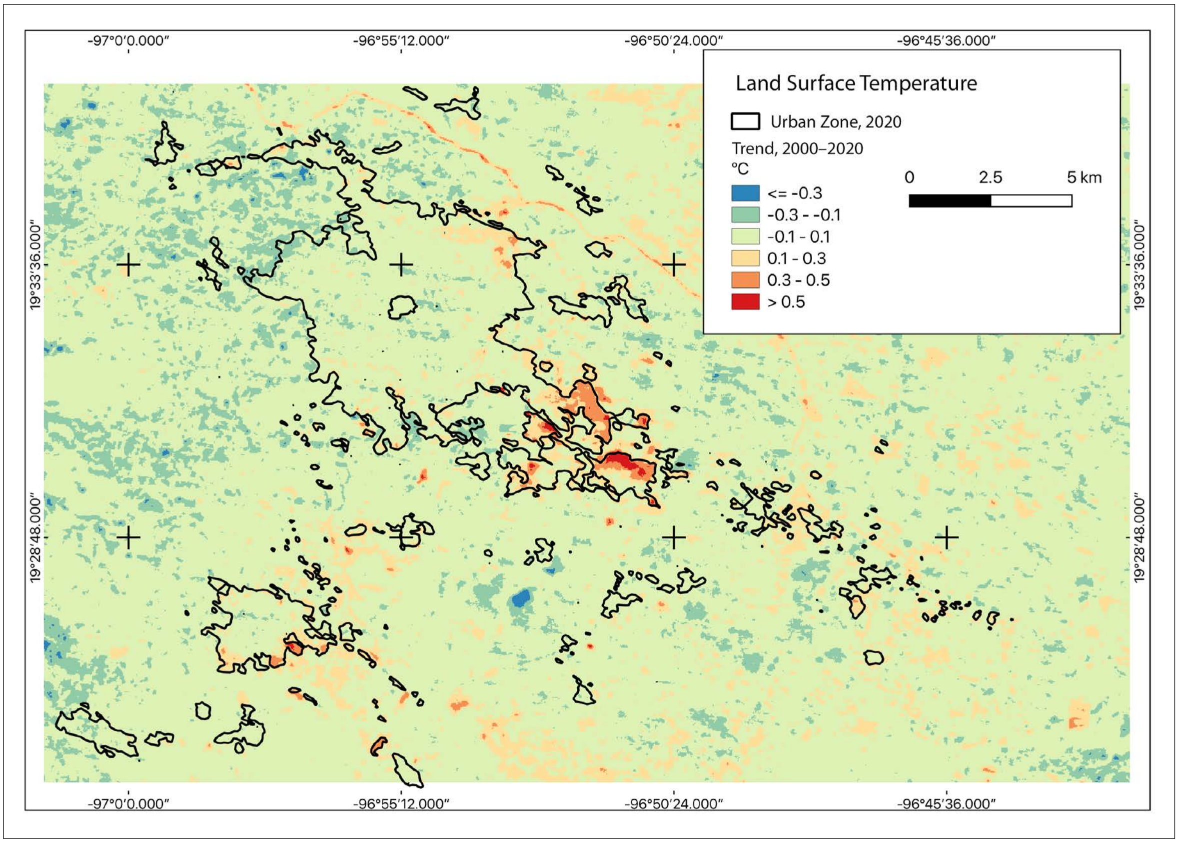

Figure 11. Trend of land surface temperature for the period 2000–2020. Source: Climate Engine (2023).

be expected, which could generate, in addition to health problems, issues in the supply of electricity and water, as well as other problems that decrease the quality of life of the local inhabitants. New forms of urban development should be implemented in which wooded areas and lakes are established, as well as government programs for the restoration and conservation of rivers and forests, parks, and medians in and around urban areas to avoid rising temperatures considered hazardous.

ACKNOWLEDGMENTS

To the Dirección General de Asuntos del Personal Academico DGAPA, for the posdoctoral fellowship provided to Nuria Vargas, to Dr. Frances Rodriguez, for her advice in the postdoc, to the Programa de Apoyo a Proyectos de Investigación e Innovación Tecnológica (PAPIIT IN 111023 Escenarios de Riesgo Climático Urbano).

REFERENCES

Azhar, M., Nicoli, D., Kucharski, F., Almazroui, M., Tippett, K., Bellucci, A., Ruggieri, P e In-Sik, K. (2020). Atlantic Ocean influence on Middle East summer surface air temperature. *Climate and Atmospheric Science*, 1-8.

Azuz-Adeath, I., González-Campos, C. and Cuevas-Corona, A. (2019). Predicting the Temporal Structure of the Atlantic Multidecadal Oscillation (AMO), for Agriculture Management in Mexico's Coastal Zone. *Journal of Coastal Research*, 2010-2026. https://doi.org/10.2112/JCOASTRES-D-18-00030.1

Barradas, V. (1987). Evidencia del Efecto. de "Isla Térmica" en Jalapa, Veracruz. *Geofísica*, 125-135.

Benitez, G. (2011). *Crecimiento de la población and expansión urbana de la ciudad de Xalapa, Veracruz* *and sus efectos sobre la vegetación and agroecosistemas.* Tesis. Manlio Fabio Altamirano, Veracruz: Colegio de Posgraduados.

García-Cueto, O., Jáuregui, E., Toudert, D. and A. Tejeda-Martínez. (2007). Detection of the urban heat island in Mexicali, B. C., Mexico and its relationship with land use. *Atmósfera*, 111-131.

Gunawardena, K., Wells, M. and Kershaw, T. (2017). Utilising green and bluespace to mitigate urban heat island. *Science of the Total Environment*, 1040-1055. https://doi.org/10.1016/j.scitotenv.2017.01.158

Higueras, E. (2009). *El Reto de la Ciudad Habitable and Sostenible.* Pamplona: DAPP.

Howard, L. (1818). *The climate of London.* International Association of Urban Climate.

INEGI-CONAPO. (2004). *Delimitacion de Zonas Metropolitanas 2000.* México, D.F.: INEGI, CONAPO, SEDESOL.

IPCC. (2000). *Emissions Scenarios.* Cambridge University Press.

IPCC. (2007). *Resumen para Responsables de Políticas en Cambio Climático: impactos and vulnerabilidad.* Cambridge University Press.

Jáuregui, E. (1993). La isla de calor urbano de la Ciudad de México a finales del siglo XIX. *Investigaciones Geográficas*, 31-39.

Jáuregui, E. (2005). Possible impact of urbanization on the thermal climate of some large cities in Mexico. *Atmósfera*, 249-252.

Jáuregui, E. (2009). The heat spells of Mexico city. *Investigaciones Geográficas* , 71-76.

Jáuregui, E. and E. Romales. (1996). Urban effects on convective precipitation in Mexico City. *Atmospheric Environment*, 3383-3389. https://doi.org/10.1016/1352-2310(96)00041-6

Jae-Heung P. and T. Li. (2018). Interdecadal Modulation of El Niño-Tropical North Atlantic teleconnection by the Atlantic Multidecadal Oscillation. *Climate Dynamics*, 5345-5360. https://doi.org/10.1007/s00382-018-4452-4

Manoli, G., Fatichi, S., Schläpfer, M. et al. (2019). Magnitud of urban heat islands largely explained by climate and population. *Nature*, 55-60. https://doi.org/10.1038/s41586-019-1512-9

Méndez, M. and V. Magaña. (2010). Regional Aspects of Prolonged Meteorological Droughts over Mexico and Central America. *U. S. Clivar Drought*, 1175-1188. https://doi.org/10.1175/2009JCLI3080.1

Méndez-Romero, E. (2017). *Alteraciones térmicas derivadas de la urbanización en la ciudad de Xalapa, Veracruz. Análisis espacial and tempral 1982-2015.* Veracruz, México.

NCAR. (2023). *NCAR Climate Data Guide*. Obtenido de https://climatedataguide.ucar.edu/climate-data/atlantic-multi-decadal-oscillation-amo

Oke, T. R. (1967). City size and the urban heat island. *Atmospheric Environment*, 769-779. https://doi.org/10.1016/0004-6981(73)90140-6

Oke, T., G., Mills, A.Christen and Voogt, J. (2017). *Urban Climates.* Cambridge University Press. https://doi.org/10.1017/9781139016476

Pérez-Córdova S. J. and Welsh, C. (2020). Evaluación de peligro por inundación en Xalapa, Veracruz, México. *UVserva*, 285-297. https://doi.org/10.25009/uvs.v0i10.2692

Pesaresi, M. and P. Politis. (23 de 07 de 2023). *Global Human Settlements*. Obtenido de GHS-BUILT-S R2023A - GHS built-up surface grid, derived from Sentinel2 composite and Landsat, multitemporal (1975-2030)European Commission, Joint Research Centre: https://ghsl.jrc.ec.europa.eu/download.php

Schwaab, J, Meier, R., Mussetti, G., Seneviratne, S., Bürgi, C. and E. Davin. (2021). The role of urban trees in reducing land surface temperatures in European cities. *Nature Communications*, 1-11. https://doi.org/10.1038/s41467-021-26768-w

SEDATU-INEGI. (2015). *Delimitación de las zonas metropolitanas de México.* INEGI.

SIEGVER. (2021). *Sistema de Información Estadística and Geográfica del Estado de Veracruz*. Obtenido de http://ceieg.veracruz.gob.mx/wp-content/uploads/sites/21/2021/06/XALAPA_2021.pdf

Tejeda, A. and F. Acevedo. (1990). Alteraciones climáticas por la Urbanización en Xalapa, Veracruz. *La Ciencia and el Hombre*, 37-48.

Tejeda, A., Pérez, M. and Méndez, I. (2020). *Un Laboratorio Natural del Clima: La Interacción Costa Montaña en el Centro del Golfo de México.* Universidad Veracruzana. https://doi.org/10.25009/uv.2271.1470

Tejeda-Martínez, A., Luyando, E. and E. Jáuregui. (2011). Average conditions of thermal stress in Mexican cities whith more than one million inhabitants in the face of climate change. *Atmósfera*, 15-30.

Vanguardia de Veracruz. (2023, 23 de junio). Presunto golpe de calor le habría arrebatado la vida a indigente. *Vanguardia de Veracruz*. https://doi.org/10.15366/philobiblion2022.16.001

Vargas, N. and V. Magaña. (2020). Warms spells and climate risk to human health in the Mxico City Metropolitan Area. *Weather, Climate and Society*, 351-365. https://doi.org/10.1175/WCAS-D-19-0096.1

Vienna, E. P. (2018). *Urban Heat Island Strategy City of Vienna.* Obtenido de https://www.lifetreecheck.eu/getattachment/2fff480d-c43d-4bb1-ab53-3ef9b0ea6e7e/attachment%22

Von Thaden, J.J., Binnqüist-Cervantes, G., Pérez-Maqueo, O. and Lithgow, D. (2022). Half-Century of Forest Change in a Neotropical Peri-Urban Lsndscape: Drivers and Trends. *Land*, 2-14. https://doi.org/10.3390/land11040522