One Ecosystem 9: e125302
doi: 10.3897/oneeco.9.e125302

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Research Article

Influence of ENSO and the urban heat island on climate variation in a growing city of the western Mexico

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Academic editor: Davide Geneletti

Received: 12 Apr 2024 | Accepted: 29 May 2024 | Published: 24 Jun 2024

Citation: Nájera González O, Nájera González A, Marceleño Flores SML, Flores Vilchez F (2024) Influence of ENSO and the urban heat island on climate variation in a growing city of the western Mexico. One Ecosystem 9: e125302. https://doi.org/10.3897/oneeco.9.e125302

Abstract

To understand climate change in the local context, it is necessary to analyse three factors in the territories; 1) how temperature and precipitation have varied over time, 2) if there is an association with the natural variation of the planet, for example with the El Niño-Southern Oscillation (ENSO) phenomenon, and 3) if the variations could be related to human actions that directly alter the climate, such as gas emissions into the atmosphere and deforestation. Understanding how these three factors interact, what impacts they have caused on the territory and how they will behave in future scenarios, allows us to think about development planning strategies that seek to adapt human communities to future climate conditions. This study addresses climate change in the City of Tepic, analysing the interannual variation of temperature and precipitation, its association with the ENSO phenomenon and the possible relationship with the urban heat island, contrasting two time periods; 1980-1999 and 2000-2018. The results showed a generalised increase of +1 ºC between periods, decrease of precipitation up to -6% the summer months and increase up to +20% the autumn months. The influence of ENSO on temperature variation increased from 10% to 20% in the most recent period, and its influence on precipitation variation decreased from 17% to 8%, respectively. On the other hand, the heat island increased its extension by more than 60% and its intensity by about 8 degrees between the periods analysed. The differences between periods are discussed descriptively in relation to the doubling of the area of urban use, population, atmospheric emissions and the loss of 30% of the forests in the areas adjacent to the city.

Keywords

climate variability, El Niño phenomenon, land-use change, climate change, cities, urban growth

Introduction

Climate is a key factor that can have a great impact on people's lives. Climate variation in a region can have significant consequences for the economy, public health, agriculture, and the environment (Monterroso and Conde 2018). For example, if an area experiences a prolonged drought, this can lead to a decrease in agricultural production, which in turn could have a negative impact on the local economy and the food security of the population. On the other hand, if an area experiences an increase in temperature, this could lead to an increase in the frequency and intensity of extreme weather events such as floods or forest fires, having consequences for biodiversity and human communities.

An increase in the frequency and intensity of climate variations has been observed throughout the world due to climate change. According to the Intergovernmental Panel on Climate Change (IPCC) (2019), this has been linked to increased emissions of gases into the atmosphere caused by human activities, such as the burning of fossil fuels, deforestation, and waste production, which in turn leads to an increase in global temperature. As a result, extreme weather events are occurring, including floods, droughts, tropical cyclones and heat waves, which can have serious consequences, like damage to infrastructure, interruptions in food and water supply, health problems and loss of human lives, among other negative environmental impacts.

Understanding climate change in the local context is fundamental to be able to take appropriate measures to address its negative effects. To this end, it is necessary to analyse three factors in the territories that allow understanding how climate variables have behaved over time and how they could behave in the future (Lobato and Altamirano 2017).

The first factor to consider is the historical variation of temperature and precipitation. It is important to take into account how the climate has evolved in the past in order to predict how it will behave in the future. These analyses seek to identify changes, in relation to the average historical values recorded; to perform them, recent temperature and precipitation data are compared with the average historical values over a given period of time, usually a year or a specific season (Amador and Alfaro 2009). If significant fluctuations are observed, this may indicate a climate trend or pattern that may have important implications for the region or ecosystem in question.

The second factor to consider is if the variation is associated with the natural variation of the planet, such as the El Niño-Southern Oscillation (ENSO) phenomenon. This phenomenon can have a significant impact on local climatic conditions, and understanding its behavior is essential to know how climatic conditions will develop in the future (Zebiak et al. 2014).

As explained by Méndez et al. (2007), this is a variation in climate patterns in a region of the Equatorial Pacific Ocean involving both sea surface temperature and surface atmospheric pressure. This variation is characterised by two phases (Carrillo et al. 2018); a positive or warming phase known as the Niño event (positive anomalies higher than +0.5 ºC) and a negative or cooling phase known as the Niña event (negative anomalies lower than -0.5 ºC). Warming or cooling in this area of the ocean can last for months or even more than a year, disrupting the normal circulation of energy in the atmosphere, resulting in changes in rainfall and temperature patterns in tropical regions of the world (Zebiak et al. 2014).

Indices are used to study ENSO, the most commonly used are the multivariate El Niño index (MEI) and the Oceanic Niño index (ONI). As described in the studies of Méndez et al. (2007) and Carrillo et al. (2018), the MEI is calculated from sea level pressure, wind speed and direction, sea surface temperature and cloudiness, observed every two months in the tropical Pacific Ocean. In contrast, the ONI is calculated from temperature anomalies in a specific region of the tropical Pacific Ocean, known as region 3.4, over three-month periods.

In Mexico, important links have been found between the ENSO phenomenon and variations in temperature (Cruz-Rico et al. 2015) and precipitation (Magaña et al. 2003; Méndez et al. 2007). In general, in Niño events, temperatures are higher than normal, while in Niña events, temperatures decrease. Regarding precipitation, Niño events increase the amount of rainfall during the autumn and winter months (between November and March), and reduce rainfall during the summer months (between June and September). On the contrary, Niña events are related to wet summers and dry winters that can extend into the spring months, causing severe droughts between March and May.

Finally, the third factor to consider is if the observed variations could be related to human actions that directly affect the climate, such as atmospheric gas emissions and deforestation. Specifically, on the theme of deforestation, several investigations argue that the decrease in vegetation cover at the micro-scale level is having an impact on local climate variability. The formation of patches on the ground in agricultural or urban areas can generate different thermal gradients, such as heat islands, which are strong enough to influence mesoscale circulation and, in the long term, cause changes in the temperature and precipitation of the regional climate (Carvajal and Pabón 2016). This fact has been confirmed in different areas of the Americas, where a correlation has been established between deforestation and the increase of urban and agricultural stain with modifications in climatic variables over a 10 year period (Pavetti et al. 2016Xian et al. 2020).

Understanding how these three factors interact, what impacts they have had on the territory and how they will behave in the future, is fundamental for thinking about planning and development strategies that allow human communities to adapt to future climate conditions. This is particularly relevant in territories where the population is concentrated, such as cities and conurbations, especially in developing areas.

This is the case of the City of Tepic, considered the most important city in the State of Nayarit, in western Mexico, since according to the National Institute of Statistics and Geography (INEGI) (2020) it is home to just over 40% of the total population of the state (INEGI, 2020). The city has experienced a rapid increase in population and urban development in recent decades, which has led to significant changes in land use and increased demand for services and resources. According to Avalos et al. (2018), between 1985 and 2015 the urban area has doubled. Affecting the surrounding forest cover, particularly the Sierra de San Juan protected natural area, important in biodiversity and vital for the ecosystem services it provides for the region.

Thus, the purpose of this research is to contribute to the understanding of climate change in the city of Tepic, analysing the annual changes in the climatic variables temperature and precipitation, its correlation with the ENSO phenomenon and possible link with the heat island due to urban growth, contrasting two time periods; 1980-1999 and 2000-2018. It is expected that the results will be useful for urban planning, risk management, public health, local economy, among other priority issues that help ensure sustainable development in the area and improve the quality of life of its inhabitants.

Likewise, it is expected to contribute to the knowledge of climate variability in growing cities and that the discussion can derive global conclusions as well as future lines of research.

Materials and methods

Area of study

As described in Avalos et al. (2019), the city of Tepic is part of the Tepic-Xalisco metropolitan area. It is located in the central area of the State of Nayarit, in western Mexico; in the so-called Matatipac valley, which is part of the Mololoa River Basin, a affluent derived from the Lerma-Santiago River (Fig. 1). It is located at an altitude of 915 meters above sea level. On the periphery of the city are 30 towns situated within a radius of 15 km, which together with the community of Xalisco account for a total of 469,152 inhabitants, 80% of them concentrated in the city of Tepic (INEGI, 2020). The area is surrounded by volcanic mountains, including the natural protected area (ANP) Sierra de San Juan, which has been declared a Biosphere Reserve at the State level (Nájera et al. 2023).

Climate data collection

As suggested by the World Meteorological Organization (WMO) 2012, we used the maximum, minimum, average and monthly precipitation temperature records of the weather stations located in the area of study that had at least 30 years of data and an availability of information of over 85% (WMO 2012). With these criteria we identified the meteorological stations available in the Climate Computing Project (Clicom) database of the National Meteorological Service (SMN), (https://smn.conagua.gob.mx). For the study area only one station was found that met the established criteria, called Tepic station; located in a central position in the urban area of Tepic, with continuous information from 1980 to 2018 and only 2.6% of missing data.

Data processing and analysis

Historical variation of climatic variables

To analyse variability we follow the exercises performed by Carrillo et al. (2018); we analyse the interannual variation of monthly averages of temperature and precipitation over 20-year periods (historical period 1980-1999 and current period 2000-2018). These time periods, longer than 10 years, are used because they allow explaining the variability in terms of global signals of natural climate variation and local changes caused by human activity, such as changes in vegetation cover (Trewin 2007).

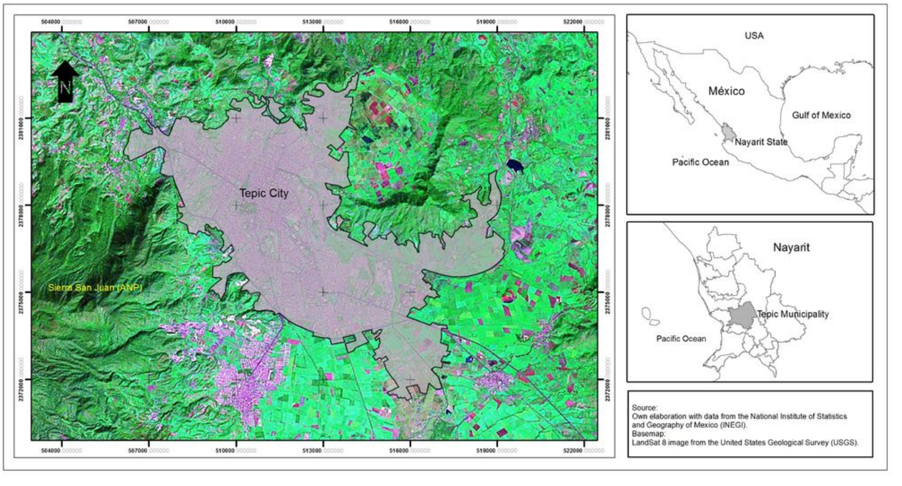

Figure 1.

Location of the City of Tepic.

Correlation with the ENSO phenomenon

To detect the connection between the ENSO phenomenon and climate variability, we used the method of Méndez et al. (2007), which consists of two steps. The first focuses on calculating the standardised monthly anomalies of the climatic variables (temperature and precipitation), using the formula: $a=[x-u(x)]/o(x)$, where x is the monthly climate variable, $u(x)$ is the average value of the month in the data set and $o(x)$ is the standard deviation of the dataset. Subsequently, in a second step, the correlation between the standardised monthly anomalies of the climate variables and the ENSO indices is calculated. In this case, it was decided to perform the correlation with the MEI index, since it is one of the most complex in its estimation and prediction.

Therefore, to be comparable with the MEI index, the standardised monthly temperature and precipitation anomalies were averaged over two-month periods. Thus, the correlation between both was calculated using Pearson's correlation coefficient (r) at a confidence level of $p\leq 0.05$. MEI values were extracted from the U.S. National Office of Oceanic and Atmospheric Administration (NOAA) database, MEI.v2 available at https://psl.noaa.gov/enso/mei.

In order to complement the correlation analysis, we used the Bayesian network method to identify specific temperature and precipitation trends during ENSO Niño and Niña events. Bayesian networks are a statistical calculation that can identify trends, even when they are not conditioned by cause and effect. Therefore, they are ideal for making predictions between climatic variables and planetary variation phenomena such as ENSO, where there is no exclusive conditioning correlation, since temperature and precipitation variability depends on multiple factors (Cano et al. 2004).

Based on probability theory, Bayesian networks seek to answer the question; what is the probability that event A behaves in such a way, given that event B happens? Being A the event to predict and B the event that happens. So, in this exercise, what is the probability that the climatic variables of temperature and precipitation will increase or decrease during positive or negative ENSO phases (Niño or Niña events)? The standardised monthly anomaly is the event to be predicted (A) and the MEI index is the event that occurs (B).

The procedure was carried out as described in the research of Nájera et al. (2023). Firts the data from A and B were segregated into quartiles to construct a probability matrix. Then, using the cells of the matrix and the values of the quartiles, we calculated the probability of A when B happens by applying the following formula: $P(A/B)=P(A\cap B)/P(B)$, where the probability that A will occur when B happens ($P(A/B)$, is equal to the events A given that B happens between the total of events ($P(A\cap B)$), divided by the result of the events B between the total events ($P(B)$). Thus, a probability value was obtained for each association of events in the matrix. Values close to 1 represent high correlation, and opposite values close to 0. The results are expressed in percentage of probability of occurrence of A given that B happens.

Lastly, statistical dependence between the condition of event *A* and *B* was corroborated by applying the following formula in each cell of the matrix: *P(A/B)-P(A)*. That means, the probability of *A* occurring while *B* happens minus the result of dividing the events *A* by the total number of events.

Negative results were transformed into positive values, since probability theory only admits positive values. Subsequently, a chi-square (X^2) test of independence, with a significance level of alpha 0.05 and one degree of freedom, was performed to determine whether the results showed statistical dependence. We considered dependent those conditions in the matrix that yielded statistical dependence values greater than 3.8, while those with values below this score were considered independent. The complete procedure for calculating statistical dependence by using X^2 can be found in the research of Cerda and Villarroel (2007).

To explain the behavior of precipitation anomalies during Niño or Niña events we use the World Meteorological Organization (WMO) (2012) precipitation classification system. Values below -2 are extremely dry, and values above 2 are extremely wet. Values between -1.5 and -1.9 are considered severely dry, values between 1.5 and 1.9 are considered very wet, and values between -0.9 and 0.9 are considered normal.

Link to the evolution of the urban heat island

To investigate the possible influence of human activities on climate variability in Tepic, we analysed the urban heat island (*UHI*). This phenomenon is characterised by elevated surface temperatures associated with the spatial expansion of a city over time.

For this purpose, the surface temperature (*ST*) was estimated from the processing of three satellite images that correspond to the analysis of the 1980-2018 time series, ensuring that the results could be contrasted with the data from the meteorological station. The images used were taken during the month of March by Landsat 5 for the year 1986, Landsat 7 for 2000 and Landsat 8 for 2018, extracted from the United States Geological Survey (USGS) portal (https://earthexplorer.usgs.gov/).

To obtain *ST*, in the image processing we used the thermal infrared bands, which corresponds to band 6 in Landsat 5 and 7 with spectral range between 10.4 and 12.5 microns, and bands 10 and 11 in Landsat 8 with spectral range between 10.6 and 11.2, and 11.5 and 12.5 microns. With a resolution of 120 meters in Landsat 5 and 7, and 100 meters in Landsat 8. The resulting values of the Landsat 8 bands were averaged, so that according to the spectral range could be comparable with the results of Landsat 5 and 7.

To visualise the *UHI*, we estimated the *ST* from the brightness temperature (*TB*), following the method and formulas described in Advan and Jovanovska (2016). The method consists of calculating the spectral radiance (*TOA*) to obtain the *TB*, and subsequently transforming the *ST* value to degrees Celsius.

The spectral radiance (*TOA*) was calculated using the formula: *TOA=ML*Qcal+AL*. Where TOA is equal to the band-specific multiplicative rescaling factor (ML), multiplied by the thermal band values (*Qcal*), plus the band-specific additive rescaling factor (AL). Both rescaling factors were extracted from the satellite image metadata.

And the brightness temperature (*TB*), through the following formula: $TB=(K_2/(ln(K_2/TOA)+1))-273.15$. Where *TB* is equal to the band-specific heat conversion constant two (K_2), by the natural logarithm (*ln*) of the result of dividing the product of the band-specific heat conversion constant one (K_1) by the spectral radiance (*TOA*), plus one. And the conversion value from Kelvin degrees to Centigrade degrees (273.15). The two heat conversion constants are obtained from satellite image metadata.

Due to the differences of the satellites and sensors of the images used, for the calculation of TOA and TB of Landsat 5 and 7 images we performed an adaptation to the method, following what is described in Ahmed et al. (2013). This adaptation bases the ST estimation on transforming the values of the digital numbers (DN) of band 6 into TOA, applying the following formula: *TOA=(LMax-LMin/QcalMax-QcalMin)*(Qcal-QcalMin)+LMin.* Where the values of *L* and *Q* were obtained from the image metadata. *QcalMin* is equal to 1, *QcalMax* is equal to 255, *Qcal* is equal to *DN*, and *LMax* and *LMin* correspond to the spectral radiances for band 6 in digital numbers 1 and 255, that is, *QcalMax* and *QcalMin*, respectively.

And from the *TOA* result, *TB* is calculated using two calibration constants, following the formula: $TB=(K_2/ln(K_1/L_v+1))-273.15$. Where the calibration constant K_1 is equal to 666.09 ($watt/m^2*ster\ \mu m$) and K_2 is equal to 1282.71 (Kelvin degrees). L_v is the TOA value expressed in $watt/m^2*ster\ \mu m$.

Finally, the *TB* result, both for Landsat 8 and Landsat 5 and 7, is obtained in Kelvin degrees. Therefore, to express the *ST* it is necessary to convert *TB* to Celsius degrees, using the conversion constant 273.15 *(ST=TB-273.15)*.

Once the TS maps were obtained, the urban patch of Tepic was delimited in each time period through a visual digitization on the image, and taking as a reference the contributions of Aválos et al. (2018) on the urban growth of the area.

Results

Interannual variation of temperature and precipitation

A sustained +1 ºC increase in temperature was observed from 1980-1999 to 2000-2018 at the Tepic weather station, going from 21.9 ºC to 22.9 ºC average temperature in the most recent period. The increase was most strongly evidenced in maximum and minimum temperatures (Fig. 2). According to the record, the maximum temperature increased by about +0.8 ºC from 29.3 ºC to 30.1 ºC, with marked increases during the winter and spring months. The minimum temperature increased by about +1.3 ºC, from 14.4 ºC in the historical period to 15.7 ºC in the current period. It should be noted that differences of more than +2 ºC in minimum temperature were observed during the autumn and winter months (October-January).

Regarding precipitation, the annual accumulated average for both periods at the Tepic weather station remained similar; 1129.8 mm and 1159.9 mm respectively. However, it decreased during the summer months between -2% and -6%, and increased between +13% and +20% during the autumn and winter months (Fig. 2).

Correlation between ENSO and climate variability

We present the results of the correlation analysis and Bayesian networks between the MEI index of the ENSO phenomenon and the standardised monthly anomalies of temperature and precipitation for the Tepic weather station.

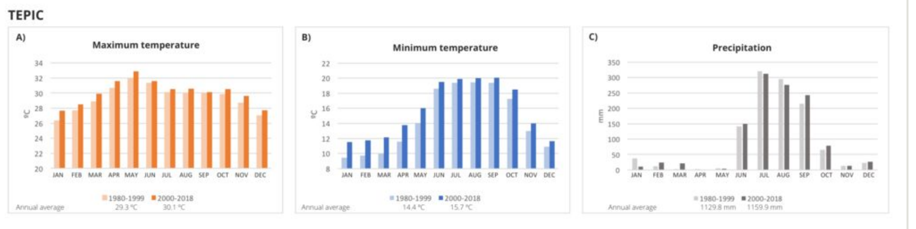

Figure 2.

Interannual variation of maximum (A) and minimum temperature (B), and precipitation (C) of the Tepic meteorological station data series.

The correlations are presented in percentage value; correlating the anomalies of the data series of the analysed period and the average anomalies of the months during the same period, coupling to two months because it is a correlation with the MEI index. We used the expression $p \leq 0.05$ to indicate statistical significance in the correlations.

Positive correlations indicate that when the ENSO anomaly value is high, the anomaly value of the temperature or precipitation variables is also high, and inversely. Thus, the Niño event during months with a positive correlation would be associated with an increase in temperature or precipitation. In the same case, a Niña event during months of positive correlation would be associated with a decrease. On the contrary, inverse correlations show that when the ENSO anomaly value is high, the temperature or precipitation anomaly is low. Thus, Niño events during months with inverse correlations would be associated with decreasing temperature or precipitation anomalies and Niña events with increasing anomalies.

In general, at the Tepic weather station, the temperature variable responds to the conditions of each phase in ENSO; Niño event associated to temperature increase and Niña event to decrease. However, the way in which it influences on the maximum and minimum temperatures differs during the months of the year and periods analysed. Fig. 3 shows the correlations between the MEI index and the anomalies of each of the climatic variables in their interannual variation for the historical period 1980-1999 and current 2000-2018.

For the maximum temperature variable, the correlation with ENSO went from -8% in the historical period to 1% in the current period, without statistical significance in both cases. The summer months presented positive correlations, high in particular the months of August and September in the historical period (49% $p \leq 0.05$), and from June to August in the current period (53%-60% $p \leq 0.05$) (Fig. 3).

While the winter months presented inverse correlations, being the months from December to March the most influential in the historical period (56%-78% $p \leq 0.05$), and the months from February to April in the current one (51%-64% $p \leq 0.05$). That is, during the summer months the maximum temperature anomalies are associated 50%-60% to ENSO, increasing during Niño event and decreasing during Niña. In the case of the winter months, the anomalies are related between 50%-70% with ENSO, indicating that the anomalies of maximum temperature decrease in these months are associated with the Niño event and those of increase with the Niña event.

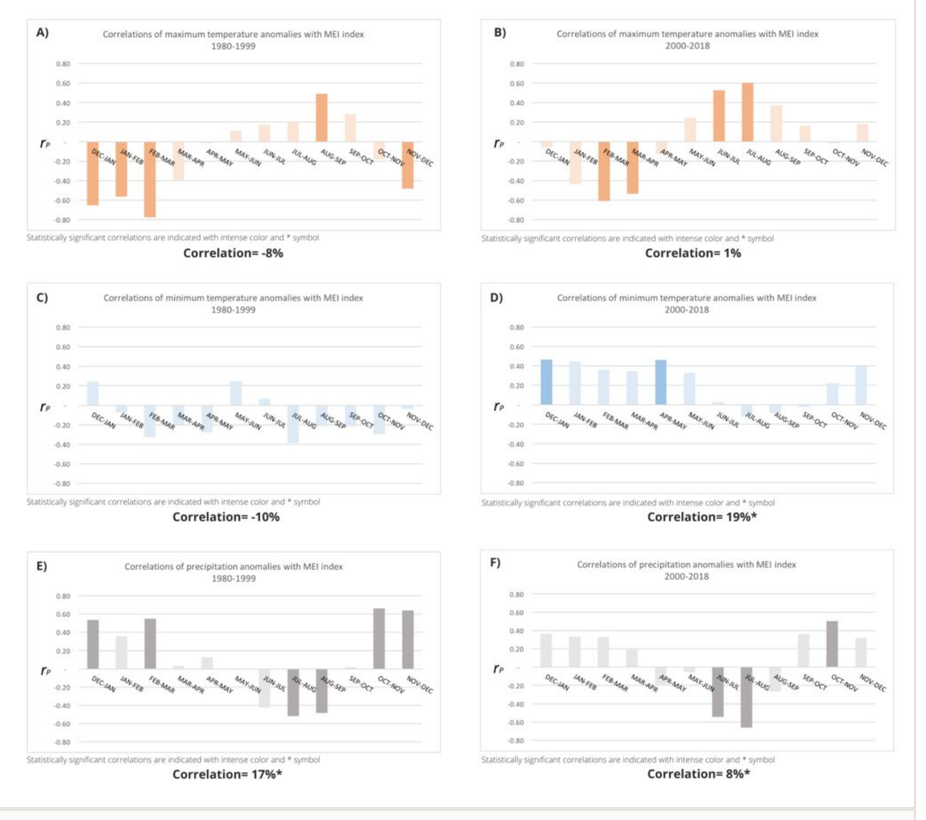

Figure 3.

Correlations with MEI index ENSO of maximum temperature (A and B), minimum temperature (C and D) and precipitation anomalies (E and F) from the Tepic meteorological station data series. Statistically significant correlations ($p \leq 0.05$) are indicated in dark color.

To complement the above, and to clarify the influence of ENSO on the maximum temperature, we analysed jointly the results of the Bayesian network exercise and the correlations of the interannual variation (Fig. 4). Different behaviors were found in the historical and current periods. In summer, there was a lower probability of maximum temperature increase during Niño; 31% historical and 11% current. And a higher probability of decrease during Niña; 15% historical and 28% current. Being June-August the most influential months, as opposed to August-September in the historical period.

TEPIC					
1980-1999			**2000-2018**		
Maximum temperature					
Maximum anomaly values +2.8 ºC and -2.7 ºC			Maximum anomaly values +3.8 ºC and -1.8 ºC		
	Niño	Niña		Niño	Niña
Summer (Aug-Sep)	31% +	15% -	Summer (Jun-Aug)	11% +	28% -
Winter (Dec-Mar)	38% -	34% +	Winter (Feb-Apr)	29% -	10% +
Minimum temperature					
Maximum anomaly values +1.1 ºC and -2.8 ºC			Maximum anomaly values +2.7 ºC and -1.4 ºC		
	Niño	Niña		Niño	Niña
Winter (Dec-Jan) and Spring (May-Jun)	8% +	24% -	Winter (Dec-Jan) and Spring (Apr-May)	34% +	23% -
Summer-Fall (all other months)	36% -	27% +	Summer (Jul-Sep)	10% -	10% +
Precipitation					
Maximum anomaly values +3.1 and -1.3			Maximum anomaly values +3.8 and -1.6		
	Niño	Niña		Niño	Niña
Winter-Fall (Oct-Mar)	31% +	24% -	Fall (Oct-Nov)	14% +	33% -
Summer (Jun-Sep)	10% -	12% +	Summer (Jun-Aug)	20% -	15% +
Note: The value of the cells in the table represents the probability that A occurs when B happens. That is, the probability that the temperature or precipitation anomaly (A) occurs when a Niño or Niña event (B) happens. The ranges of the maximum anomalies in each period and the climatic variable are specified. Example of interpretation; in the period 1980-1999 there was a 31% probability of maximum temperature anomalies of up to +2.8 ºC during the Niño event.					

Figure 4.

Results of the Bayesian network exercise for the Tepic weather station data series. Conditions with statistical dependence are indicated in shaded color.

In winter, the probability in the current period during both events was lower, with a 29% decrease in maximum temperature during Niño (38% historical) and a 10% probability of increase during Niña (34% historical). The months of February-April were particularly noticeable, while in the historical period it was the months of December-March. Similarly, differences were found in the amplitude of the anomaly; +2.8 ºC and -2.7 ºC in the historical period, and +3.8 ºC and -1.8ºC in the current period. In all cases the probabilistic conditions were dependent.

With respect to the minimum temperature variable, the differences between periods were more accentuated; an inverse correlation was obtained -10% in the historical period and a positive correlation of 19% in the current period (Fig. 3). Regarding the differences in the interannual correlation, while in the historical period the winter months had an inverse correlation between -20% and -40%, in the current period they behaved with a positive correlation between 30% and 45%. The winter-spring months had the highest correlation, specifically December-January and April-May (45% $p \leq 0.05$). On the other hand, the summer months in both periods presented inverse correlations of around -20% but without statistical significance.

In summary, while in the past the minimum temperature anomalies were inversely related to the ENSO anomalies, the most recent data indicate that the behavior was modified, being now positively correlated; when the ENSO anomaly increases or decreases, the minimum temperature anomaly also increases or decreases. However, considering the interannual variation of the recent period, the influence of ENSO is more evident in the winter-spring months.

As a result of the Bayesian network exercise, it was found that in the winter-spring months there is a higher probability of minimum temperature increase during Niño; 8% historical and 34% current. A similar in probability of decrease during Niña event; 24% and 23%. In contrast, the influence in the historical period was pronounced in the months December-June, and in the current period in the months December-May.

In the case of the summer months, during both events, the values for the current period were lower than the historical. During El Niño there was a 10% probability of a decrease in minimum temperature and during Niña a 10% probability of an increase, accentuated during the months of July-September. While in the historical period it was 36% and 27% respectively, accentuated during the summer and autumn months. As in the maximum temperature, the amplitude of the minimum temperature anomaly also increased, going from +1.1ºC and -2.8ºC to +2.7ºC and -1.4ºC in the current period. It is important to note that these probabilistic conditions were dependent, with the exception of the historical period in winter-spring.

Finally, for the precipitation variable, a decrease in the influence of ENSO was found, being 17% in the historical period and 8% in the current period ($p \leq 0.05$) (Fig. 3). For the two periods the positive correlations resulted in the winter and spring months (October-March) and the inverse correlations in the summer months (June-September). The months October-November coincided as those with the highest positive correlation, and July-August as those with the highest inverse correlation.

This means that during the Niño event, precipitation would be expected to increase during the autumn months of October-November (possible torrential rains) and the winter months of January-March (winter rains). On the other hand, the summer months from June to September would decrease (possible drought). In the case of the Niña event, precipitation would decrease during the winter and spring months from December to March and increase during the summer months from June to September.

However, it is noteworthy that in the current period the October-November correlation was lower than in the historical period; it decreased from 67% to 50% ($p \leq 0.05$). On the contrary, the inverse correlation the months of July-August increased from 52% to 66% ($p \leq 0.05$), influence extending from the months June-July with 54% correlation ($p \leq 0.05$). Focusing on the current period, the highest ENSO influence in Tepic occurs in summer from June to August, causing possible droughts during the Niño event and torrential rains during the Niña event.

Bayesian network analysis provided strong evidence for the observed changes in precipitation patterns related to ENSO. The analysis revealed an increase in the probability of reduced precipitation during El Niño events in recent years. Specifically, the current probability of decreased precipitation during summer El Niño events is 20%, compared to the historical value of 10%. In contrast, La Niña currently has a 15% chance of increasing precipitation, compared to 12% historically. In addition, the influence of ENSO on the precipitation calendar has also changed. In the past, ENSO mainly affected the months of July to September. However, in current years it has focused on the months of June to August.

The impact of ENSO on autumn and winter precipitation has also changed. Historically, these phenomena influenced precipitation from October to March. Currently, the influence appears to be concentrated in October and November. Also, the analysis revealed changes in the probability of precipitation associated with ENSO events. El Niño events in autumn and winter currently have a 14% probability of increased precipitation, compared to 31% historically. And during Niña events 33% probability of precipitation decrease, compared to 24% of the historical period.

Significant differences in the range of anomalies have also become evident. In the past, conditions ranged between +3.1 and -1.3, indicating extremely wet and normal conditions, respectively. In contrast, at present, the anomalies range between +3.8 and -1.6, representing severely dry and extremely wet conditions. However, it is important to note that not all probabilistic conditions were dependent, as shown in Fig. 4.

In synthesis, the data for the current period reveal that the ENSO phenomenon has a stronger and significant influence on precipitation decrease anomalies, which can lead to severely dry conditions. These conditions are observed during the Niño events in summer and Niña in winter, with a probability of 20% and 33%, respectively. On the other hand, the influence of ENSO on precipitation increase anomalies was found to be minor, but still significant; during the Niño events in autumn-winter and Niña in summer exist a 14% and 12% probability of experiencing extremely humid conditions.

Analysis of UHI growth

Resulting from the surface temperature analysis, through the interpretation of satellite images taken in the month of March 1986, 2000 and 2018, we found variations in the temperature ranges and their surface extent (Fig. 5). In general, we observed a continuous increase in the ST range and surface extent corresponding to high and very high temperatures.

ST Range	1986	Area	2000	Area	2018	Area
Very low	20.1-25.3 ºC	7.1%	26.2-31.2 ºC	4.3%	27.4-33.3 ºC	7.1%
Low	25.4-27 ºC	30.6%	31.3-33.9 ºC	28.1%	33.4-35.3 ºC	22.1%
Medium	27.1-29 ºC	36.4%	34-35.8 ºC	33.3%	35.4-36.9 ºC	37.6%
High	29.1–31.4 ºC	16.7%	35.9–38.4 ºC	27.5%	37-38.8 ºC	27.1%
Very high	31.5–36.9 ºC	9.2%	38.5–43.9 ºC	6.8%	38.9-45.3 ºC	6.1%
Urban area extension		2,477.9 ha		3,193.3 ha		5,665.05 ha

Figure 5.

Surface temperature (ST) of the City of Tepic and its evolution in the periods 1986, 2000 and 2018. The ST data were grouped into ranges according to minimum and maximum values in each period. The surface extent of each ST range is expressed as a percentage in relation to the total area of the urban area in each time period analysed.

Regarding the amplitude of the ST ranges, in 1986, the oldest year recorded, the ST varied between 20.1 ºC and 36.9 ºC, with a difference of 16.8 degrees between the minimum and maximum range. In 2000, an increase in this range was observed, with minimum values of 26.2 ºC and maximum values of 43.9 ºC, representing a variation of 17.7 degrees between the extremes. This implies an increase of approximately 6.1 to 7 degrees compared to the minimum and maximum ST values recorded in 1986.

In the most recent period of 2018, a less pronounced increase was recorded. During this year, the ST ranged from 27.4 ºC to 45.3ºC, with a variation of 17.9 degrees between the extreme values of the ranges. This represents an increase of approximately 1.2 to 1.4 degrees compared to the values recorded in 2000.

The surface extent of the ST ranges is related to the growth of the urban patch. It was observed that the urban area increased twice its size between the oldest and the most recent analysed period, being especially pronounced its increase by 43.6% from 2000 to 2018 (Fig. 6).

We refer to the heat island phenomenon by analysing the surface area corresponding to the very high ST range in each year of study. In this sense, an increase in both the surface area and the heat island range was observed.

In 1986, the UHI covered 9.2% of Tepic's surface, with temperatures ranging between 31.5 ºC and 36.9 ºC. However, the most frequent temperatures in 67% of the city were between 25.4 ºC and 29 ºC.

In 2000, the extent of the UHI decreased, but its intensity increased. It affected 6.8% of the urban area, with a temperature range that went from 38.5 ºC to 43.9 ºC. During this period, the predominant surface temperatures in the city were between 31.3 ºC and 35.8 ºC.

In 2018, continuous trends were observed in relation to the UHI, which covered 6.1% of its total area, with a temperature range varying between 38.9 ºC and 45.3 ºC. At first sight, these statistics may seem similar to those recorded in 2000. However, it is essential to take into account the urban growth experienced by the city during this period.

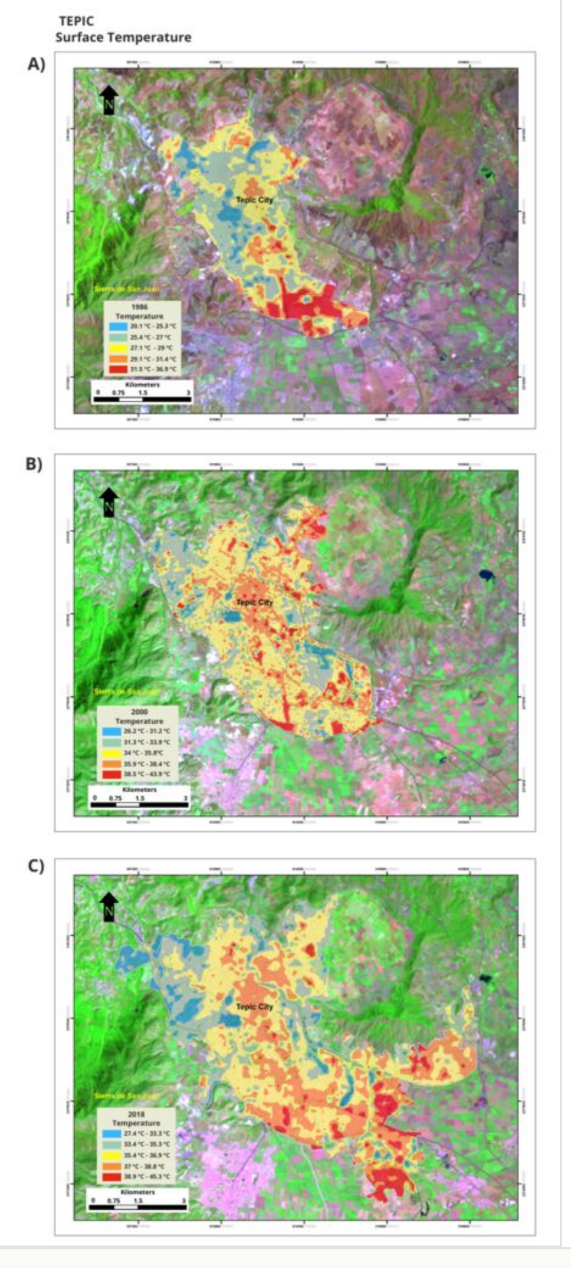

Figure 6.

Surface temperature (ST) of the City of Tepic and its evolution in the periods 1986 (A), 2000 (B) and 2018 (C). The ST data were grouped into ranges according to minimum and maximum values in each period. The surface extent of each ST range is expressed as a percentage in relation to the total area of the urban area in each time period analysed.

When considering urban growth, it is revealed that the 6.1% heat island surface area recorded in 2018 is equivalent to 345.5 hectares, while the 6.8% recorded in 2000 was equivalent to 217.1 hectares. This implies that the heat island experienced an increase of 62.8% between 2000 and 2018, in terms of its surface area.

According to spatial location, in 2000 the heat island was mainly concentrated in the central zone of the city. However, in 2018, in addition to the central zone, very high temperatures were observed in the southeast region, coinciding with the area where the greatest urban growth has been experienced.

Discussion

How is the increase in UHI related to climate variability?

To answer this question, we have to start from two facts. On the one hand, the heat islands generated by the urban ground, depending on their extension and temperature, can generate thermal gradients that influence the normal circulation of heat flow in the atmosphere, and cause long-term changes in temperature values. On the other hand, vegetation cover absorbs thermal radiation and provides humidity to the environment, creating a kind of microclimate capable of offsetting the influence of global climatic phenomena, such as ENSO, which affect the local temperature and precipitation patterns. The above explanation adds to the reflections derived from research by Carvajal and Pabón (2016) in Latin America, and Xian et al. (2020) in North America.

In this sense, as the extent of the heat island increases, the presence of green areas decreases, which reduces protection against the effects of external climatic phenomena and their impacts on local conditions.

According to climate data, in the City of Tepic we observe a possible relation between the increase of the heat island and a higher influence of ENSO. This link is evidenced mainly in the climatic variables of temperature, where in general we found an increase in the influence of ENSO from 10% in the historical period to 20% in the most recent period. This increase also correlates with an increase in the extent of the UHI, which remained stable in the historical period from 1986 to 2000, but experienced a growth of more than the double area between 2000 and 2018.

These findings suggest a direct connection between the increase of the heat island and a higher ENSO influence in the City of Tepic. However, more detailed research and additional analyses are needed to fully understand this relation and its implications for urban climate in the region.

As discussed in the literature review by Grajeda et al. (2023), the heat island and surface temperature of cities is conditioned to different causes, among them those related to urbanization. The choice of building materials with a high capacity for heat absorption, such as asphalt and concrete, intensifies its effect. These materials retain heat during the day and release it slowly at night, raising nighttime temperatures.

Associated with urbanization is the rise in electricity consumption, especially during the warmer months. This generates a vicious circle, since energy production also releases heat into the atmosphere.

In addition to other aspects such as vehicular congestion and the use of fossil fuels by public and private transportation release greenhouse gases and particulate pollutants that intensify the problem. The reduction of parks, gardens, green areas and natural runoff areas such as wetlands and rivers affects the natural balance of the urban ecosystem, limiting its capacity to regulate temperature and humidity.

The causes of this problem are closely related to the consequences. The increase of the heat island in a city has several negative impacts; higher electricity demand to support thermal comfort and food refrigeration equipment leads to an increase in greenhouse gas emissions, but also to higher expenses in the family economy. With high temperatures, drinking water is used more intensively for personal use and irrigation, which can generate stress on water resources. Heat waves, intensified by the heat island effect, can have serious health consequences, especially for vulnerable groups such as the elderly and children. In addition to other effects on the physical integrity of citizens due to poor air quality and limited green areas or natural recreation zones.

These consequences have already been evidenced for the Citiy of Tepic.Serafín 2019 Serafín (2019) and Alatorre and Llanos (2020) have explored air quality problems related to emissions from vehicular load in the city. Mejía and Gómez (2015), the lack of green areas and its social implications. The conclusions of these authors point to the need to plan urban growth, oriented to sustainable urban development, which allows habitability under future climate conditions. However, these are investigations that have not been directly related to heat islands or climate variations.

Implications of temperature and precipitation variation in the City of Tepic

The generalised increase of +1 ºC in maximum and average temperature in Tepic, and +2 ºC in minimum temperature in autumn-winter, will have implications on plant evapotranspiration and thus its function of dissipating part of the heat generated by solar radiation. These conditions could be accentuated during the summer months, when precipitation is expected to decrease by up to -6%. To this must be added the climate impacts associated with the change in land use in the region, with natural areas being replaced by cropland and human settlements.

The increase in precipitation of up to 20% in the autumn months will exacerbate flooding problems in the City of Tepic. This is due to the limited natural capacity for absorption and conduction of rainwater, as a result of the obstruction of natural watercourses and construction in inadequate areas that increase the risk of flooding. In addition, the drainage infrastructure, which is more than 50 years old, is deficient and insufficient in the face of increasingly intense storms, causing overflows in sewers and urban rivers that cause flooding. These problems are a consequence of Tepic's unplanned urban growth, a common and recurrent case in Mexico and other developing countries (Zaragoza and Guzmán 2023).

In general, these temperature and precipitation conditions can affect the comfort and well-being of the city's inhabitants, reducing the habitability of outdoor spaces. In addition to health problems, such as an increase in viral and epidemiological diseases, allergies, gastric diseases, psychological problems and violence (Cuerdo-Vilches et al. 2023).

Climate variation can have implications for the ecological dynamics of the ecosystems surrounding the city (including surrounding protected natural areas), affecting the distribution of species, biogeochemical cycles, altering phenological patterns and thus the interactions between species. These implications transcend to the different ecosystem services in the area, which can be affected and therefore impact human wellbeing. In particular, we highlight the ecosystem services provided by the Sierra de San Juan protected natural area in maintaining the local climate (Nájera et al. 2023).

Final considerations and limitations

Further research is needed in the climatic analysis of Tepic. The main limitation of this research was the shortage of climatic data, which puts into question the resulting analysis and the possibility of comparisons with other areas of the country. Nevertheless, the results obtained from this study are a first approach to understand the problems of climate variation and place the subject as a precedent for the development of future research.

We suggest discussing the results of climate variability with the interaction of different phenomena. Such as the influence of the Pacific Decadal Oscillation (PDO) on the local climate in the short, medium and long term. The link of precipitation trends in Tepic with the patterns of rainfall behavior in the Mexican Altiplano region. And the impact of the monsoon and hurricanes on the intensity and frequency of extreme weather events.

Regarding the heat island issue, it will be necessary to continue research to complement the results obtained with a monthly monitoring analysis for observing specific variations with greater precision. In addition to other studies, such as the generation of an inventory with specific information on urban green areas, and in situ temperature measurements to detect the absorption capacity and heat reflectance of the different surfaces of the city.

It should be considered that this research made only one observation of the urban heat island in three historical years, to complete the analysis it would be necessary to make annual observations in ten-year time periods and thus make a statistical correlation. Therefore, up to this point the discussion of the urban heat island and its connection with climate variability in Tepic are descriptive and limited to the observations made. Furthermore, we recommend the inclusion of future climate scenarios in the analysis to enhance the practical implications of this research for long-term urban planning.

While the current study offers valuable insights from its focus on Tepic, its conclusions may not be directly applicable to other cities due to geographical and climatic variations. However, the methodology employed presents a valuable opportunity for further research.

By replicating this methodology in multiple cities with diverse climates, urban forms, and geographical contexts, researchers can assess the generalizability of the findings and identify potential variations in the dynamics of urban heat islands. This broader understanding would be crucial for developing effective mitigation strategies applicable to a wider range of urban environments.

Finally, this research will hopefully highlight the importance of expanding the network of meteorological stations in order to continue monitoring temperature and precipitation variables in the coming years. We expect this to be sufficient justification for decision makers to invest in increasing climate action research. Accurate climate data are essential for urban planning, resource management and climate change adaptation.

Conclusions

We analysed the annual changes of the climatic variables temperature and precipitation of Tepic, a growing city in western Mexico. The analysis was performed over 20-year periods, with 1980 - 1999 as the historical period, and 2000-2018 as the most recent. We found differences between both periods; a generalised increase of +1 ºC in temperature and up to +2 ºC in minimum temperatures, and a reduction of precipitation of -6% in the summer months and an increase of +20% in the autumn months.

The variations of temperature and precipitation anomalies were related to the ENSO phenomenon through the MEI index, finding that the influence of the phenomenon on temperature variation increased from 10% to 20% in the current period, with the Niño events associated with temperature increases and the Niña events with decreases. Precipitation influence decreased from 17% to 8%. However, the amplitude of the anomaly in the current period is higher, which means that although its influence decreased, the intensity with which it influences increased, leading to severely dry periods during Niño events in summer and Niña in winter, and extremely humid during Niño in autumn-winter and Niña in summer.

To explain the variations in climatic variables, we decided to analyze the evolution of the UHI. We found that in comparison with the oldest period, the extension of the UHI has increased by 60%, as a result of the demographic growth that the city has experienced in the last 20 years. In the most recent date, some areas of the city show a surface temperature higher than 45 ºC, which represents 8 ºC more than the maximum range observed in the historical date.

These climate variations can affect the city's habitability, comfort, and public health. Ecosystem dynamics around Tepic might be impacted, affecting species distribution, biogeochemical cycles, and therefore their ecosystem services that generate human well-being.

In summary, the findings of this study suggest a connection between the growth of UHI and an increased influence of ENSO on the climate of Tepic. This link is observed in the temperature data, with an increase in ENSO influence from the historical to the recent period, coinciding with the expansion of the UHI. Further research is needed to fully understand this relationship and its implications.

Finally, we point out the need for urban planning as an essential tool in the coming years, as a way to build climate change resilient cities in developing countries such as Mexico.

Acknowledgements

We are thankful to the Universidad Autónoma de Nayarit for the funds to publish this research, which is the result of the call for University Productivity through Research 2023, a resource from the Patronage to Administer the Special Tax Destined to the Universidad Autónoma de Nayarit.

Hosting institution

Universidad Autónoma de Nayarit

Conflicts of interest

The authors have declared that no competing interests exist.

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