Hindawi
Advances in Meteorology
Volume 2021, Article ID 9919167, 12 pages
https://doi.org/10.1155/2021/9919167

Research Article

Seasonal Changes in Climate Variables in Rainfed Crop Areas in the Lerma-Chapala-Santiago Basin, Mexico

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Received 31 March 2021; Revised 27 August 2021; Accepted 20 September 2021; Published 13 October 2021

Academic Editor: Luis Gimeno

This paper shows the effects of changes in the spatial-temporal behavior and phase shift of climate variables on rainfed agriculture in the Lerma-Chapala-Santiago Basin in central Mexico. Specifically, changes in rainfall (R), maximum temperature (Tmax), and minimum temperature (Tmin) were analyzed over two 25-year periods (1960 to 1985 and 1986 to 2010). Climate surfaces were generated by interpolation using the thin-plate smoothing spline algorithm in the software ANUSPLIN. Climate data were Fourier-transformed and fitted to a sinusoidal curve model, and changes in amplitude (increase) and phase were analyzed. The temporal behavior (1960–2010) indicated that rainfall was the most stable variable at the monthly level and presented no significant changes. However, Tmax increased by 2°C in the final period, and Tmin increased by 0.7°C at the end of the final period. The basin was discretized into ten rainfed crop areas (RCAs) according to the extent of changes in the amplitude and phase of the climate variables. The central and southern portions (55% of the area) presented more significant changes in amplitude, mainly in Tmin and Tmax. The remaining RCAs were smaller (14.6%) but presented greater variation: the amplitude of the Tmin decreased in addition to showing a phase shift, whereas Tmax increased in addition to showing a phase shift. These results translate into a delay in the characteristic temperatures of the spring and summer seasons, which can impact the rainfed crop cycle. Additionally, rainfall showed an annual decrease of approximately 50 mm in all RCAs, which can affect the phenological development of crops during critical stages (emergence through flowering). These changes represent a significant threat to the regional economy and food security of Mexico.

1. Introduction

In recent decades, the increased presence of greenhouse gases in the atmosphere has caused a gradual increase in temperatures around the world, resulting in global warming. Global warming has, in turn, modified certain climate patterns, such as atmospheric circulation, and led to greater variability in climate conditions, resulting in more extreme climate conditions and changes in seasonal climate [1–3]. These changes are reflected as changes in the spatial and temporal behavior of rainfall and temperature, which can alter the global energy balance and water availability and have important repercussions for ecosystem functioning [4, 5].

Several studies have confirmed changes in climate seasonality, especially in rainfall [6] and temperature [7] records. These changes impact the phenology and physiology of plant species and affect their distribution [8]. Undoubtedly, one of the most concerning effects of these changes in seasonality is the impact on crops in rainfed agricultural systems given its direct repercussions on local and global food security. At the global level, 80% of crops are produced in rainfed systems [9], including more than half of major staple foods such as wheat, rice, and maize [10]. In Mexico, according to the agricultural, livestock, and forest census [11], only 10.8% of agricultural lands are irrigated, whereas 83% are rainfed (and 6.2% are combined irrigation and rainfed systems). Maize is one of the most important crops and has the most extensive cultivation area (78% of the total crop area) in the country.

Climate studies are often complex because weather data are usually limited or available in the form of point data only, which may not be sufficient for the large-scale analysis of climate phenomena. However, geographic information systems (GISs) have facilitated the spatial and temporal analysis of climate. These systems can be used to generate climate surfaces based on the interpolation of climate data recorded by weather stations using different geostatistical methods with the aim of estimating climate data for areas where data are unavailable with the highest possible certainty [12]. Spline interpolation is an efficient interpolation method for this purpose. Using spline interpolation, diagnostic statistics can be obtained to measure and assess the fit of climate data to a given area [13]. This method is used by WorldClim (http://www.worldclim.org/) to generate regional climate information and to construct climate models and scenarios [14]. It has been shown to be effective in comparison to other models [15] and has been widely used to generate spatial-temporal climate data at different scales in order to improve the understanding of changing climate and its effects on ecosystems.

The Lerma-Chapala-Santiago Basin (LCSB) is one of the most important and extensive basins in Mexico, representing 6.8% (134,038 km^2) of the country's area. It intersects portions of the states of Mexico, Querétaro, Michoacán, Guanajuato, Jalisco, Aguascalientes, Zacatecas, Durango, and Nayarit (see Figure 1). It has a population of 19,495,769 inhabitants and a population density three times higher than the average of 145 inhabitants per km^2. The Lerma-Santiago River is one of the longest rivers in Mexico. It originates in the state of Mexico (Mexican highlands), intersects the Santiago River, discharges into the Asadero River, and finally flows into the Pacific Ocean in San Blas, Nayarit [16].

The LCSB has economic and social significance at the national level because of its extensive agricultural and industrial activities [17, 18]. However, it is one of the basins with the highest level of environmental deterioration in Mexico [19]. Its main tributary, the Lerma River, is one of the most contaminated water streams in Mexico [20]. Competition for water for different uses is constant due to the rapid growth of urban areas and the water demand of agricultural production, which could eventually lead to a state of crisis [21].

Twenty-two million hectares of land are planted with crops in Mexico, of which 15.8 million hectares are rainfed [22]. There are 2.8 million hectares of rainfed crops planted in the LCSB, 18.2% of the national total. The main rainfed crops are maize (33.7%), beans (10.1%), forage maize (7.2%), forage oats (3.8%), pastures and grassland (3%), and sorghum (2.5%), which represent a little more than 60% of the rainfed crops in the area. The remaining 40% consists of more than 100 other produce.

Rainfed crops are largely dependent on the rainfall received during the rainy season. According to the Mexican National Meteorological Service [23], the rainy season of the LCSB normally begins during the second half of May and lasts until the end of October, and the dry season begins in November and ends in April. Rainfed crops are mostly cultivated during two cycles, the spring/summer cycle and fall/winter cycle, with nearly three-quarters being cultivated during the spring/summer (54%) or fall/winter (17%) [24].

The aim of the present study was to generate spatial-temporal series of the climate variables of rainfall (R), maximum temperature (Tmax), and minimum temperature (Tmin) by month from 1960 to 2010 in central Mexico (the Lerma-Chapala-Santiago Basin) and to analyze changes in these variables over time. In particular, changes in seasonality were assessed through analyzing changes in the amplitude (α) and phase (φ) of the climate variables in rainfed cultivation areas (RCAs) in order to locate agricultural areas where production may be threatened. Finally, the suitability of thermal conditions per phenological and plant development stage of maize was analyzed based on growing degree days (GDDs).

2. Materials and Methods

2.1. Methodological Development. Figure 2 details the method used in the present study.

2.2. Processing of Climate Data and Generation of Climate Layers. The climate databases of the Climate Computing Project (CLICOM) of the National Meteorological Service of Mexico were used (see Figure 2A). The study period from 1960 to 2010 was considered because consistent data were available. Also, the World Meteorological Organization recommends that a minimum period of 30 years be considered to characterize the climate change of a region [25]. Data from a total of 1,576 meteorological stations between 23° 26′ 2.4″ N and 104° 18′ 21.5″ W and 19° 4′ 4.8″ N and 99° 20′ 38.4″ W were used.

The process involved the construction of explanatory models using the dependent variables (one at a time) of R, Tmax, and Tmin and the independent variables of elevation, longitude, and latitude. For elevation, the digital elevation model (DEM) of the SRTM Digital Elevation Database version 4.1 of NASA was used and rescaled to a resolution of ≈200 meters [26].

The interpolation of climate variables and generation of the climate surfaces were carried out in the ANUSPLIN software version 4.3 based on the polynomial regression of the dataset, in this case, longitude, latitude, and altitude data. To validate the interpolated surfaces of the climate variables, we calculated the square root of general cross-validation (RTGCV) statistic, which includes the mean square root error [27].

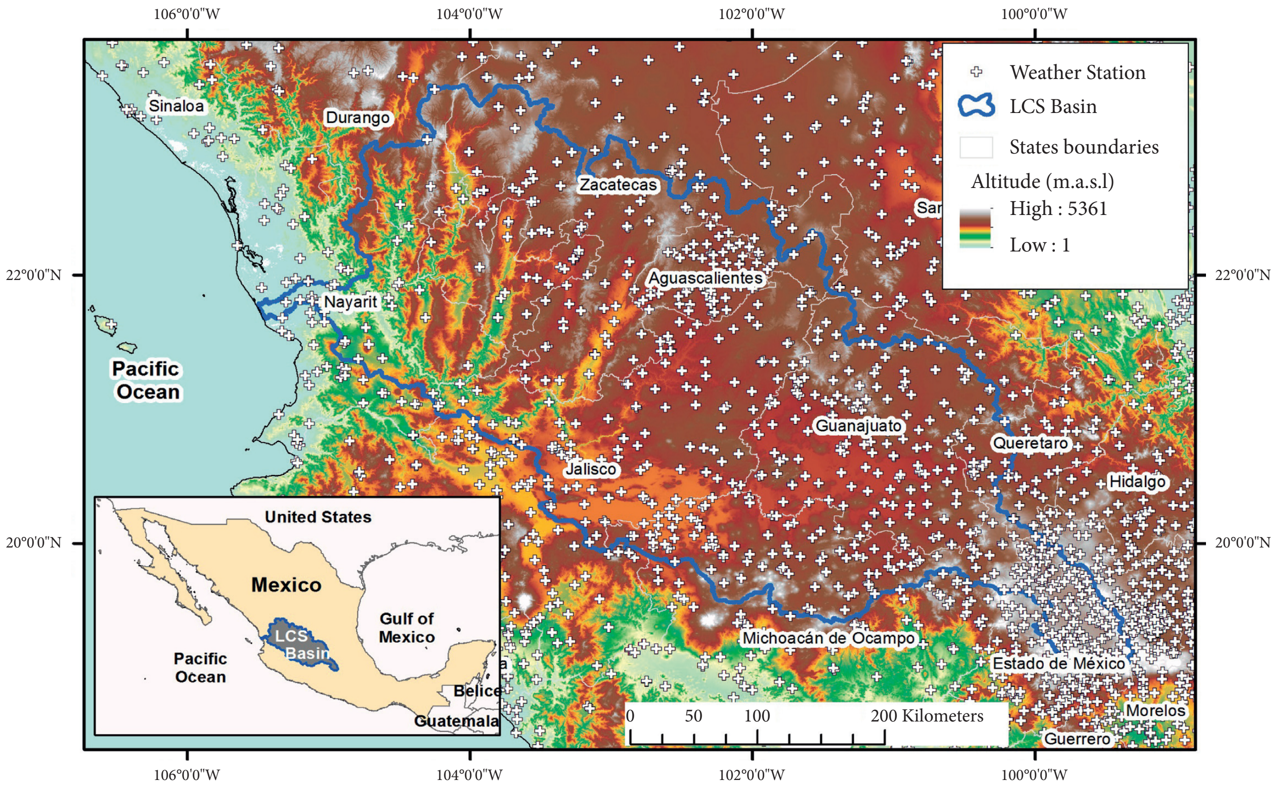

Figure 1: Lerma-Chapala-Santiago Basin.

2.3. Seasonal Analysis. In the seasonal analysis (see Figure 2B), time series were generated for the three climate variables from raster-format images (∗.rst) using the *Seasonal Trends Analysis* tool in the software TerrSet [28]. This application enables the analysis of seasonal trends by fitting climate data to sinusoidal curves through Fourier transformation, enabling a data conglomerate to be simplified and expressed in terms of sine and cosine (equation (1)) as follows:

$$y = a_0 + \sum_{n=1}^{n=2} a_n \sin\left(\frac{2\pi nt}{T}\right) + b_n \cos\left(\frac{2\pi nt}{T}\right) + e, \quad (1)$$

where y is the value of the series, a_0 is the mean of the series, a_n is the amplitude, b_n is the phase shift ranging from 0 to 360°, t is the time of each harmonic, n is the number of harmonics, T is the time of the total series (2π), with π equal to 3.1416, and e is the error term [29].

The software simplifies the interpretation of a shift between an initial and final curve. The period was divided into two halves, where 1960–1985 represented the initial period and 1986–2010 the final period. The amplitude (see Figure 3(a)) refers to an increase in the value of the measured variable (+) in the final period or, vice versa, a decrease (−) in the final period. The phase is considered as the angular velocity of the curve in the final period (1986–2010) with respect to the curve in the initial period. In other words, if the final curve shifts to the right with respect to the initial curve, a positive sign (+) is assigned, indicating a delay in the behavior of the variable; conversely, if the final curve of the final period shifts to the left, a negative sign (−) is assigned, indicating an advance (see Figure 3(b)).

The trend analysis was based on the Mann-Kendall test [30]. It estimates the significance of changes between values of −1, 0, or +1, which indicate a decreasing trend, lack of trend, or increasing trend, respectively, over the course of the analyzed time series. Areas with significant ($p < 0.05$) tendencies were identified, and the amplitude (α) and phase (φ) profiles of each climate variable (R, Tmax, and Tmin) were extracted for those areas. The RCAs that experienced the most significant changes were identified as shown in Figure 2C.

The behavior of α and φ can vary over space and time and show a positive and/or negative trend. A positive trend in amplitude ($+\alpha$) reflects an increase in the variable, and a negative trend ($-\alpha$) reflects a decrease. In regard to phase behavior, a positive trend ($+\varphi$) indicates that the maximum values of the variable present a delay and, conversely, a negative tendency ($-\varphi$) indicates that the maximum values of the variable present an advance. Both shifts indicate loss of seasonality or a mismatch between the required temperature and water conditions of crops or ecosystems and the actual temperature and rainfall conditions.

2.4. Growing Degree Days (GDDs). As mentioned above, maize is one of the most important rainfed crops in the study region, covering 33.7% of the RCA. For this reason, the GDDs were calculated for maize, and the possible impacts of changes in the amount of heat received during the phenological stages were explored.

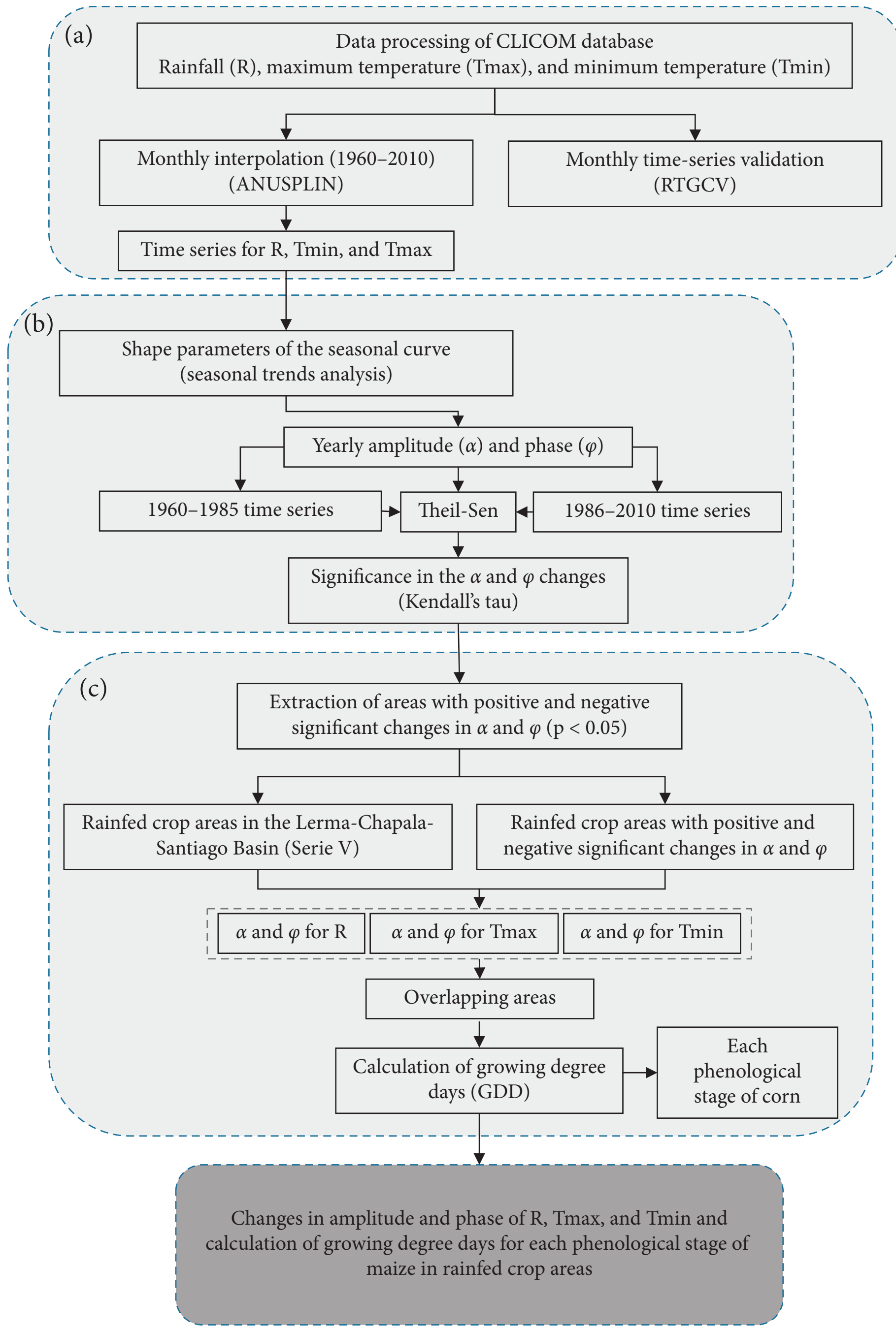

Figure 2: Methodological diagram.

The GDDs (see Figure 2) were calculated to determine the amount of heat required by plants for favorable development during different phenological stages from germination to maturity based on the maximum, minimum, and basal temperatures. Plants that receive a quantity of heat under the threshold values cannot adequately develop or reproduce (<10°C) [31]. The GDDs were estimated according to the following equation [32]:

$$\text{GDDs} = \frac{(T\,\text{min} + T\,\text{max})}{2} - \text{Tbase}, \qquad (2)$$

where GDDs are the growing degree days, Tmin is the minimum temperature, Tmax is the maximum temperature, and Tbase is the base temperature (10°C).

First, the reference GDD values were obtained for the stages of emergence (Ve), vegetative growth (V10), flowering (VT), filling of ears (R1), and maturity (R6) [33]. Then, the mean Tmax and Tmin were calculated for all of the RCAs in the study area to calculate the actual GDDs. These values were compared to the reference values to analyze the change in both the initial and final periods.

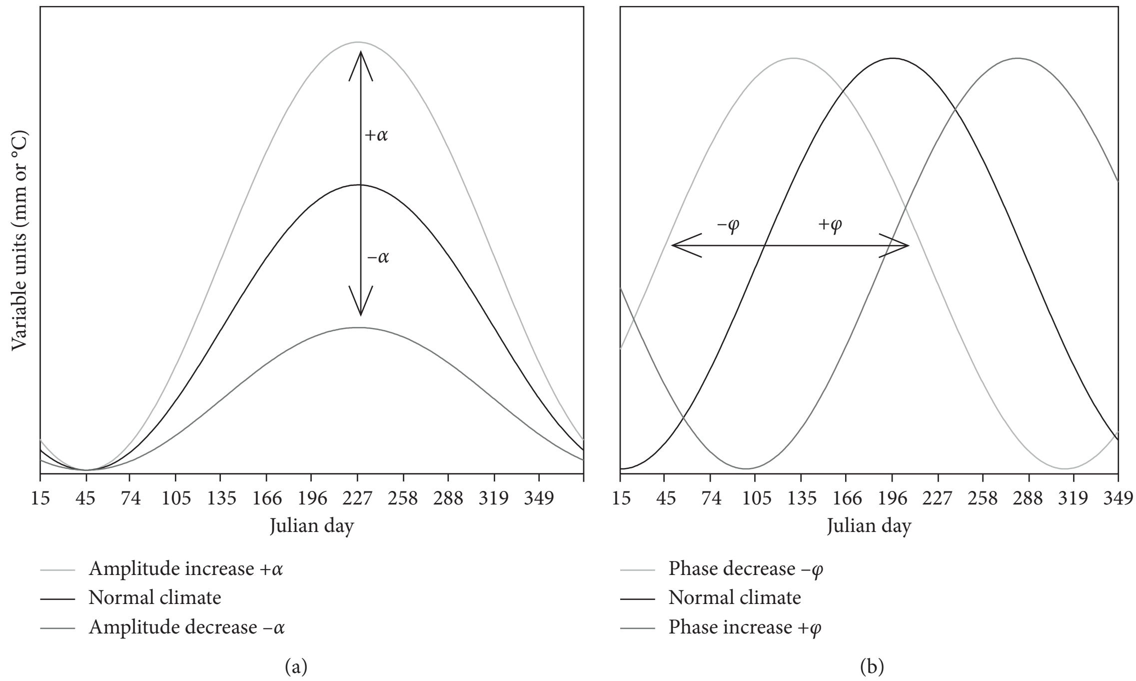

Figure 3: Interpretation of (a) amplitude (α) and (b) phase (φ).

To calculate accumulated degree days (ADDs), the following equation was used:

$$\text{ADDs} = \sum_{i=1}^{n} \text{GDD}_i, \quad (3)$$

where n is the number of days evaluated per stage and i is the day.

3. Results and Discussion

3.1. Interpolation Validity. The RTGCV of the climate interpolations of the study area indicated seasonal variability (see Figure 4). The range of values is in agreement with other studies [34] and within the normal range of the analyzed variables [35]. Thus, it can be considered that the spatial interpolations had a good fit.

In particular, rainfall (R) showed higher variability (Wilcoxon = 61441, $p = 0.00$) in the monthly mean in the latter period ($M = 20.62$, SD = 7.15) compared to the base period ($M = 16.81$, SD = 4.95). The highest error variation occurred during the summer for both periods (see Figure 4). Tmax, similar to Tmin, presented the highest error during winter (Tmax = 2.6°C and Tmin = 2.5°C); the error decreased during summer (Tmax = 2.2°C and Tmin = 2.1°C). Remarkably, for the three climate variables, the error was higher during the final period (1986–2010) ($R = \pm 0.55$, Tmax = ±0.30, and Tmin = ±0.26) compared to the initial period (1960–1985) ($R = \pm 0.21$, Tmax = ±0.21, and Tmin = ±0.23), indicating changes in regional climate variability (see Figure 4).

3.2. Changes in Amplitude (α) and Phase (φ) in the LCSB. With respect to positive trends in amplitude (α) and phase (φ) (see Table 1), the amplitude of Tmin (+αTmin) increased over 12% of the area ($p < 0.05$), and a delay in the start of summer (+φ Tmin) was observed over 10.4% of the area ($p < 0.05$). Tmax increased in terms of amplitude (+αTmax) and phase (+φ Tmax) over a smaller area (3.7% and 4.1% of the area, respectively, $p < 0.05$). With respect to rainfall, the behavior was more stable, and the percentage change was lower than that of temperature: amplitude (+αR) increased over 1.9% and phase (+φ R) over 2.9% of the area ($p < 0.05$). However, the negative tendencies in amplitude ($-\alpha$) spanned a larger area: Tmin ($-\alpha$Tmin) decreased over 25.5% of the area, and rainfall ($-\alpha$R) decreased over 19.6% of the area, affecting the quantity of rain and heat received over a large portion of the study area. However, with respect to phase ($-\varphi$ R and $-\varphi$ Tmin), no significant changes were found.

These changes could affect the phenological stages of crops. The most notable change was the negative trend in the amplitude (α) of all three climate variables (R, Tmax, and Tmin). With respect to phase (φ), a positive tendency was found (+φ), indicating that the characteristic R, Tmax, and Tmin of summer experienced a phase shift or delay, which could impact plant growth at the beginning of the crop cycle.

3.3. Changes in Amplitude (α) and Phase (φ) in Rainfed Crop Areas. The majority of the RCAs are located in the southeastern portion of the basin. Overall, the RCAs cover 38.6% of the LCSB. These areas showed significant changes in the amplitude and phase tendencies of R, Tmin, and

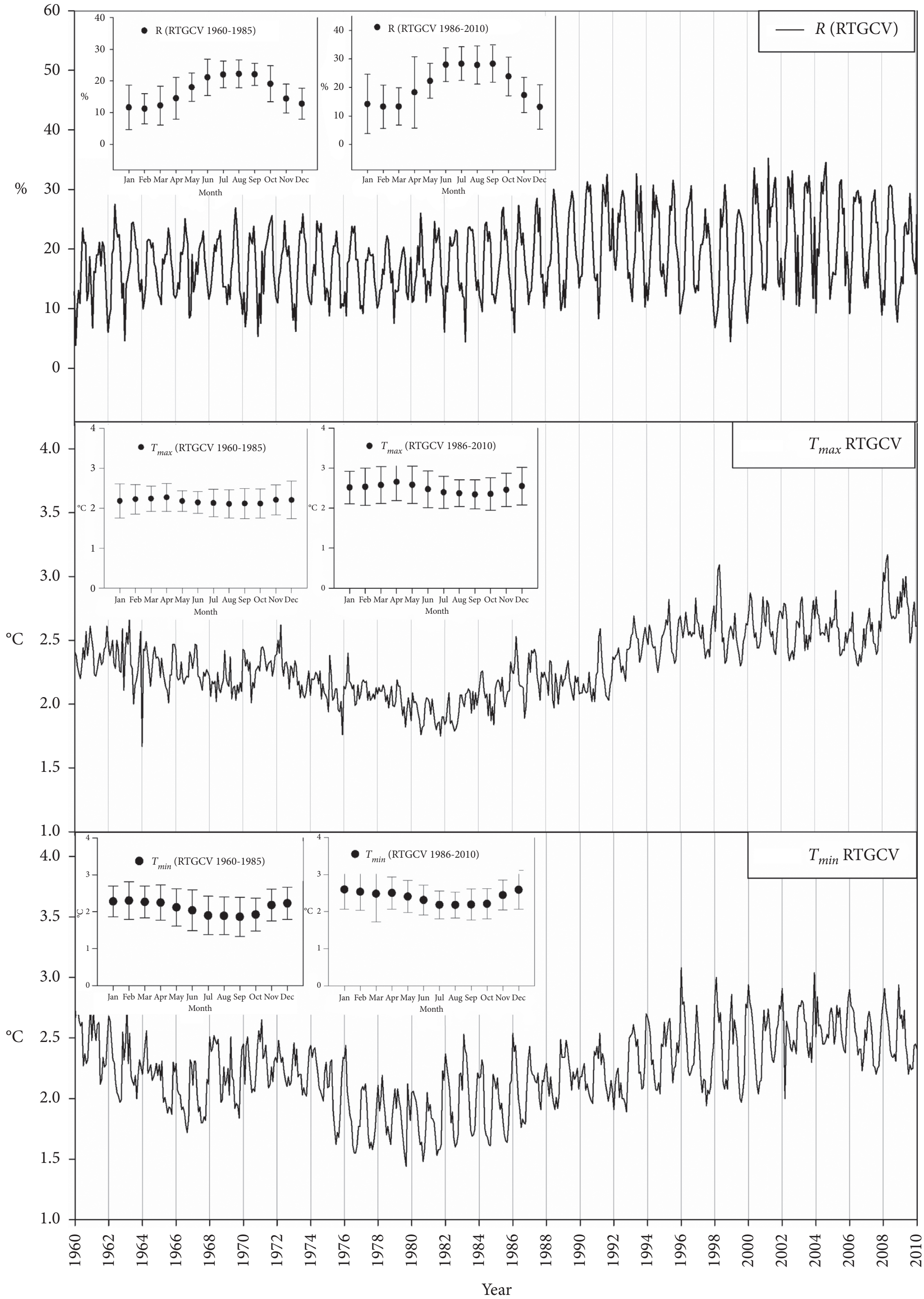

Figure 4: RTGCV of monthly R, Tmax, and Tmin for the entire study period and the initial and final periods (1960–1985 and 1986–2010) in the Lerma-Chapala-Santiago Basin.

Tmax: sixty-five percent of the rainfed crop areas (25% of the LCSB) experienced a change in seasonality ($p < 0.05$) (see Figure 5).

Both rainfall and temperature are important for the vegetative growth of rainfed crops. Several authors [30–36] have stated that each phenological crop stage has specific

Table 1: Changes in amplitude and phase of climate variables in the LCSB from the initial period (1960–1985) to the final period (1986–2010).

Trend	Variable	Amplitude (α) Affected area (km^2)	%*	Range	Phase (φ) Affected area (km^2)	%*	Range
Positive ($p < 0.05$)	p	959.6	1.9	(0.01–0.41)	1494.3	2.9	(0.01–0.27)
	Tmax	1901.3	3.7	(0.01–0.32)	2109	4.1	(0.01–0.26)
	Tmin	6192.6	12.0	(0.01–0.045)	5371.4	10.4	(0.01–0.32)
Negative ($p < 0.05$)	p	10133.8	19.6	(−0.43–0.01)	0	0	0
	Tmax	3839.8	7.4	(−0.35–0.01)	2768.1	5.4	(−0.01–0.35)
	Tmin	13180.7	25.5	(−0.62–0.01)	16.6	0.03	(−0.01–0.23)

*Percentage of significance.

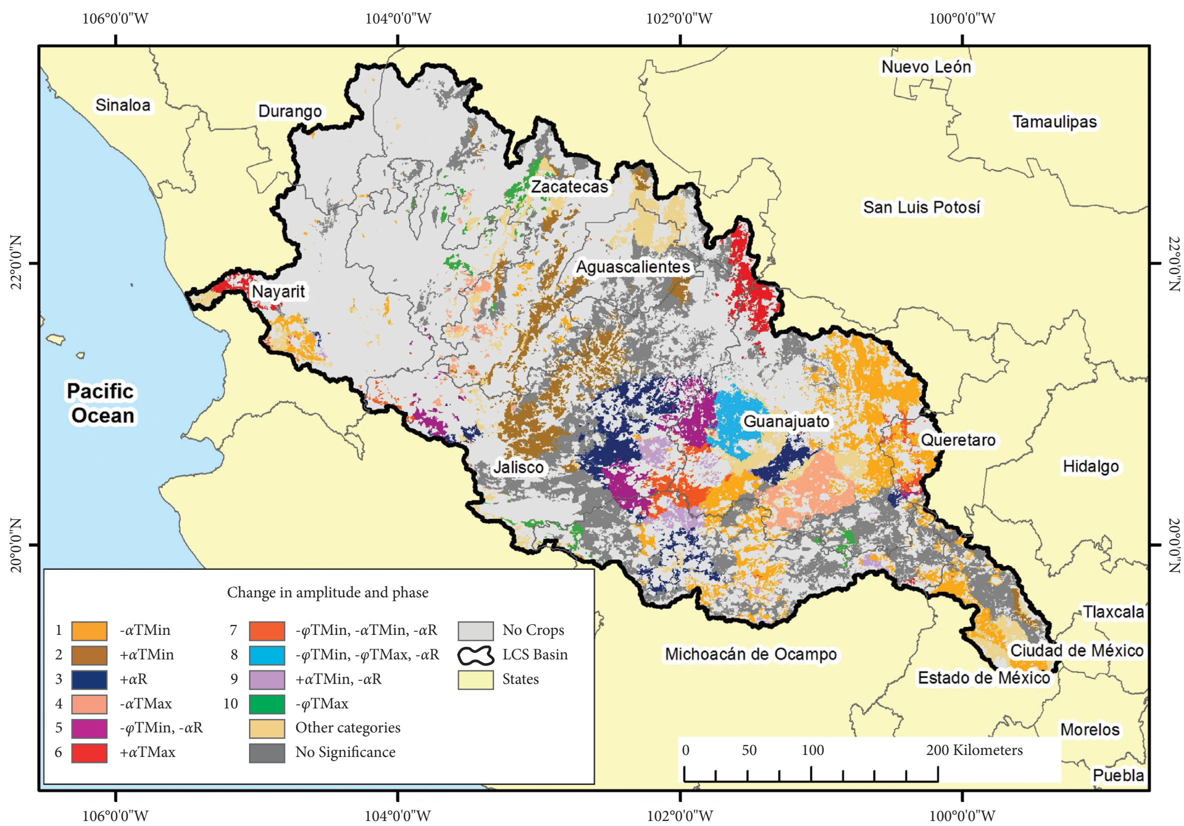

Figure 5: Changes in the amplitude (α) and phase (φ) of the climate variables in the rainfed crop areas of the LCSB (1960–1985 to 1986–2010).

thermal requirements. If these requirements fail to be met, phenological development can be delayed, and temperatures higher than adequate can damage sensitive crops. In the present case, significant changes in amplitude (α) and phase (φ) of climate variables with respect to the normal spring-summer crop cycle are presented in Figure 6 [37, 38]. The most relevant change was the advance of higher temperatures before planting, which could affect some stages, for instance, vegetative growth [39]. Rainfall (R) increased significantly with respect to the final period (1986–2010) between days 227 and 258 of the crop cycle in some RCAs; however, RCAs 3, 5, 7, 8, and 9 showed a rainfall deficit at the end of the period, which could lead to a delay in some development stages (see Figure 6).

Overall, in RCAs 1, 2, 5, 6, 8, and 9, Tmin was above 10°C in the latter period, which could be due to a temperature limit conducive to the undamaged growth and maturity stages of plants [40]. In RCAs 4 and 6, Tmax increased from 25 to 32°C in the latter period; the vegetative development stages could actually be favored by temperatures. However, in RCA 4, the Tmax exceeded values in the final period in days following vegetative development, where increased temperatures would result in damaged crops. In RCA 6, temperatures decreased in the final period, which could result in a delay in the initial and final stages of the crop, causing the crop cycle to lengthen. In RCAs 8 and 10, Tmax reached an optimal range for vegetative development, but there was a phase shift in the months of highest temperature, which could affect vegetative growth [38].

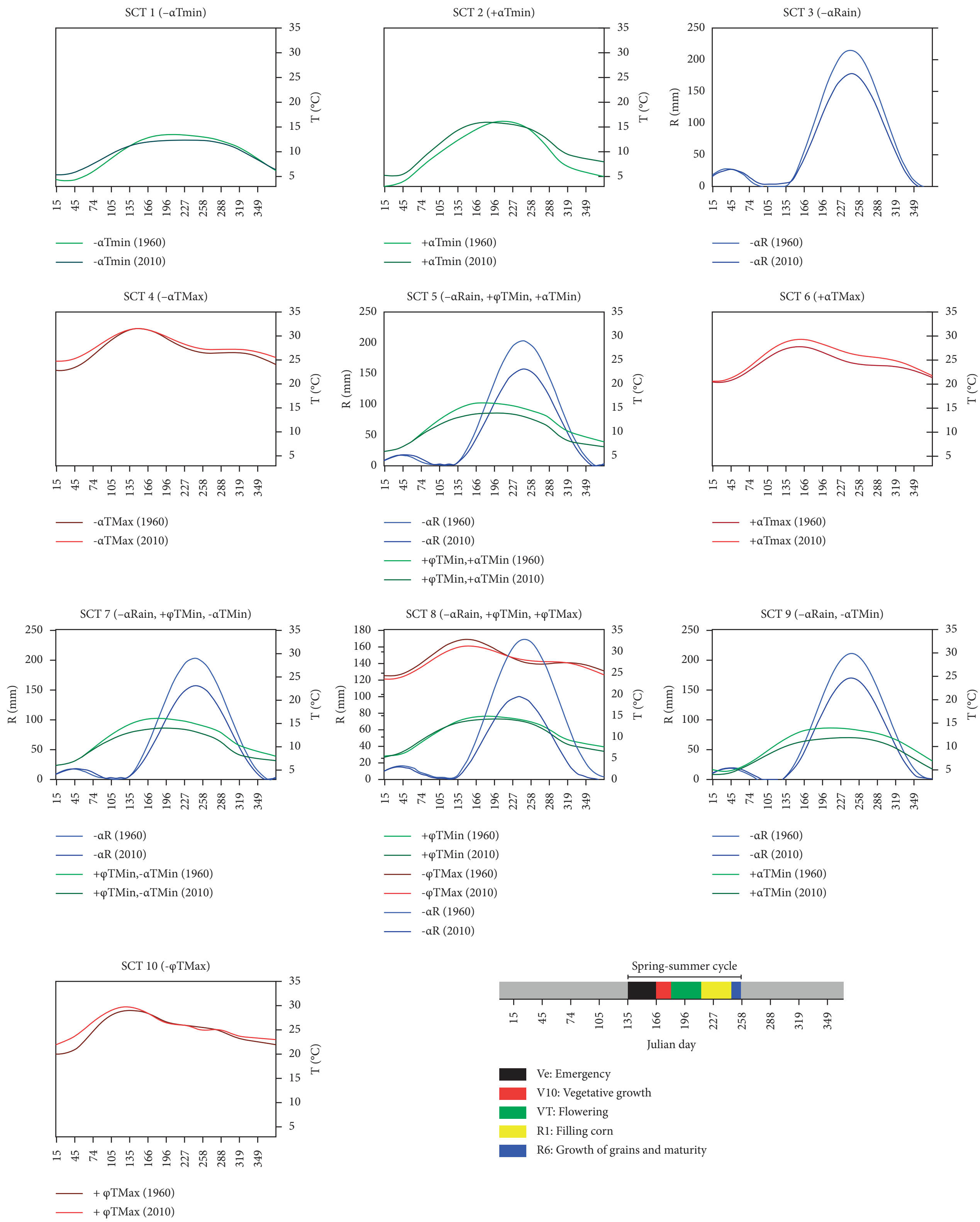

Figure 6: Significant changes in the amplitude and phase of the climatic variables by RCA with respect to the phenological development of the crops for 1960 (1960–1985) and 2010 (1986–2010).

Notably, RCAs 5, 7, 8, and 9 presented the largest changes in the three climate variables. However, these could be favorable for plants during the flowering and maturity stages, although not necessarily during the emergence and vegetative growth stages [31–38]. The initial phenological stages have specific water and thermal requirements. If these requirements are unmet, the crop cycle can lengthen, increasing the time required for crop development and production. However, considering the diverse rainfed crops present in the basin, it is difficult to identify which are affected or favored because, as previously mentioned, each crop has different requirements. For this reason, only maize is considered here because of its importance at the national level.

The changes in the climate variables between the initial 1960–1985 (reference) and the final period (1986–2010) and possible consequences for maize rainfed crops are detailed in Table 2 for all 10 RCAs. The most notable changes can be described as follows.

RCA 1 showed a decrease in Tmin of 1.12°C, whereas RCA 2 showed an increase of 0.54°C. RCA 3 showed a decrease in R of 32.71 mm. RCA 4 showed the smallest amount of change, a decrease in Tmax by 0.01°C. The aforementioned RCAs are located in the central portion of the basin, where the development of crops could be impacted by rainfall and temperature deficits (see Table 2).

RCA 6 showed a notable change in temperature, with higher peaks in the months of May and June, 1.46°C higher than that in the reference period. These months are crucial months for the soil preparation stage up through the vegetative growth stage. Although this area only represents slightly more than 1% of the total study area, nearby areas could also be affected (see Table 2).

RCA 8 presented a change in all three climate variables. This area experienced a 32-day delay in Tmin and a 12-day advance in Tmax in addition to a 69 mm decrease in rainfall, which could affect the vegetative development of some crops and make the area vulnerable to losses in crop production due to the alteration of the thermal and rainfall regimes (see Table 2).

RCA 9 presented a decrease in Tmin of 2.17°C, and a 4 mm decrease in R. An increase in Tmin can accelerate the phenological development of crops, although the combination of warmer temperatures and rainfall deficit can reduce the yield of some crops [41, 42] (see Table 2). Finally, RCA 10 showed a phase change of 8 days in Tmax. This could affect the phenological phases of some crops and lead to slower crop (maize) development [36–39].

3.4. Accumulated Degree Days (ADDs) per Phenological Stage of the Maize Crop Cycle. The ADDs per phenological crop stage decreased in the second period (see Figure 7). In other words, the quantity of heat characteristic of summer in the initial period, which favors the vegetative development of maize, decreased in the second period. It is important to note that the yield of maize crops largely depends on the filling of the ears (R1) stage [43].

In the emergence stage (Ve), some RCAs (1, 2, 4, 5, 6, and 10) achieved ADDs near the requirement (108°D) in both periods. However, in the later period, the temperatures decreased in some RCAs, which could cause a delay in this first stage. The required value was exceeded in RCAs 7, 8, and 9 in both the initial and final periods, which could result in crop damage.

The ADDs (670°D) required for vegetative growth (V10) were not achieved in RCAs 1, 4, 6, 9, and 10 during the initial or final period. This stage is sensitive since it requires the highest amount of heat or temperatures between 8 and 38°C [39]. The ADDs were achieved in the remaining RCAs (2, 5, 7, 8, and 9); thus, the vegetative growth of crops in these areas was likely maintained.

In the flowering stage (VT), the ADDs decreased in the latter period (1986–2010) in some RCAs (1, 2, 4, 5, 6, and 10) but still exceeded the required value of 816°D. The flowering process mainly depends on pollination. On the other hand, an increase in the ADDs could lead to the dehydration of pollen and, consequently, a reduction in maize yield [36]. In RCAs 7, 8, and 9, high heat accumulation was observed in both periods, up to 1,090, 1,563, and 1,004°D; in this case, crops could suffer damages due to the high amount of accumulated heat.

With respect to the filling stage (R1), RCAs 2 and 5 had ADDs close to the requirement (928°D) in the initial period. However, in the final period, the temperature decreased in both RCAs, which could mean that maize will require more time to fill or fail to achieve an adequate kernel size. Likewise, in RCAs 1, 4, 6, and 10, the ADDs are lower than the reference value in both periods. In contrast, in RCAs 7, 8, and 9, the required values were exceeded, which could negatively affect maize filling due to a decrease in pollen as a result of increased temperature (see Figure 7) [44].

Finally, during kernel maturation (R6), RCAs 2 and 5 presented ADDs close to the reference value in the second period, whereas RCAs 1, 4, 6, and 10 presented values below the reference value, which could cause a delay in the maturation of kernels. In RCAs 7, 8, and 9, the ADDs exceeded the requirement in both the initial and final period; in this case, crops could have also experienced damage before kernel formation. In fact, the rainfed production systems of these latter three RCAs are the most vulnerable; despite the decrease in temperature in the second period, the required temperature range was still exceeded (see Figure 7). Also, the cultivation of maize is often accompanied by the cultivation of other rainfed crops. Because of its structure, maize is often used as shade for these crops. Therefore, if maize is affected, other crops can also be damaged [45].

The ADDs per phenological stage in most of the RCAs decreased in the final period with respect to the initial period, as shown in Table 3. The decrease in temperature can affect maize quality. In particular, RCAs 5, 7, and 9 presented the most notable decrease in the later growth stages; kernel formation and maturation can take longer than required in the initial period. These changes may affect pollen formation and, consequently, kernel maturation.

Table 2: Seasonal behavior for changes in R, Tmax, and Tmin in the basin and possible consequences for rainfed maize crops (1960–1985 to 1986–2010).

Seasonal change in LCS basin with crops					
Seasonal change		Affected area (km^2)	Area (%)	Detected difference	Possible consequences of detected changes
RCA	$-\alpha$Tmin	8890	6.6	1.12°C	Accelerated vegetative growth
RCA 2.	$+\alpha$Tmin	4482	3.3	0.54°C	Delayed vegetative growth
RCA 3.	$-\alpha$R	3243	2.4	32.71 mm	Crop damage due to water deficit
RCA 4	$-\alpha$Tmax	2324	1.7	0.01°C	Slowed vegetative growth during final stages
RCA 5.	$+\varphi$ Tmin, $-\alpha$R	1972	1.5	20 days, 46 mm	Negative effect on plant development
RCA 6.	$+\alpha$Tmax	1620	1.2	1.46°C	Negative effect on initial growth stages
RCA 7.	$+\varphi$ Tmin, $-\alpha$Tmin, $-\alpha$R	1493	1.1	17 days, 2.31°C, 46 mm	Crop alteration during initial and final stages, including crop damage
RCA 8.	$+\varphi$ Tmin, $-\varphi$ Tmax, $-\alpha$R	1444	1.1	32 days, 12 days, 69 mm	Crop alteration during initial and final stages, including crop damage
RCA 9.	$-\alpha$Tmin, $-\alpha$R	1258	0.9	2.17°C, 41 mm	Crop damage due to water deficit
RCA 10.	$-\varphi$ Tmax	969	0.7	8 days	Negative effect on initial growth stages
Other categories		5764	4.3	S/D	
Crops with significant changes		**33460**	**25.0**	S/D	
Crops without significant changes		**18183**	**13.6**	S/D	
No crops		**82395**	**61.5**	S/D	

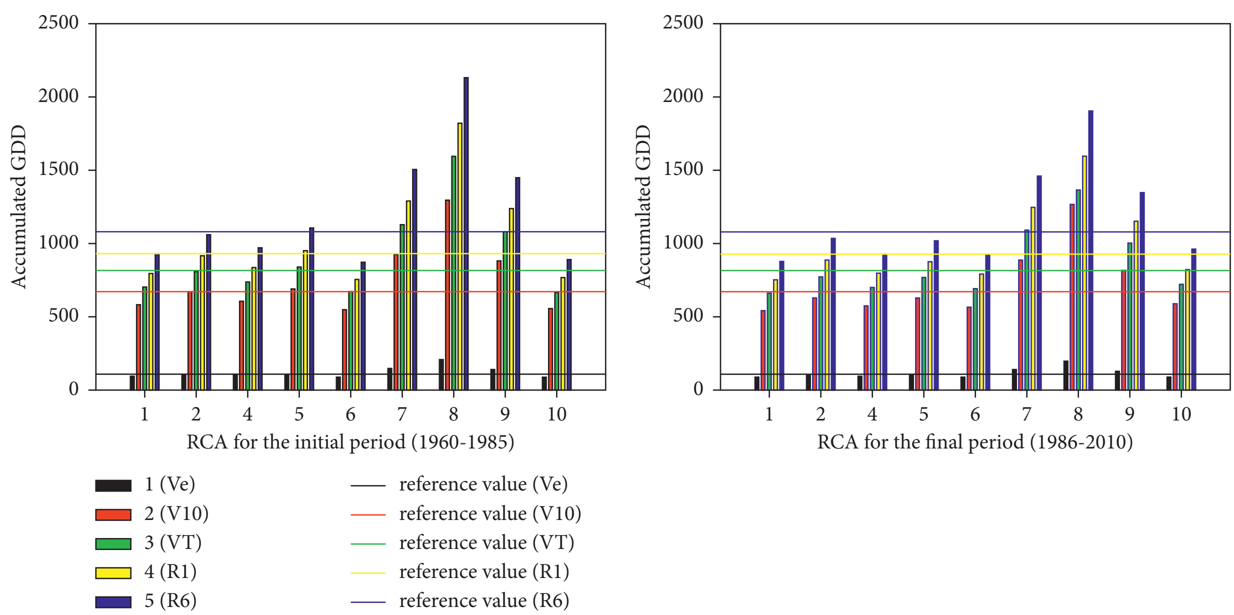

Figure 7: Accumulated degree days per phenological stage in the RCAs. Ve: emergence, V10: vegetative growth, VT: flowering, R1: filling of ears, R6: maturity.

Table 3: Differences in accumulated degree days between the initial (1960–1985) and final period (1986–2010).

RCAs	1 (Ve)	2 (V10)	3 (VT)	4 (R1)	5 (R6)
1	−6.6	−39.2	−42.4	−43.4	−42.5
2	−7.7	−32.7	−31.2	−28.5	−24.9
4	−5.8	−32.4	−35.7	−37.7	−40.9
5	−10.2	−59.7	−69.5	−76.3	−85.7
6	1.6	16.7	27.5	37.5	49.3
7	−6.5	−33.8	−38.5	−41.8	−47.6
8	−6.7	−28	−27.8	−26.4	−25
9	−10.4	−63.4	−75.9	−85.1	−97.6
10	2.8	34.2	48.2	59.6	73.3

Ve: emergence, V10: vegetative growth, VT: flowering, and R1: filling of ears R6:Maturity.

4. Conclusions

The RCAs of the LCSB experienced significant changes in the amplitude and phase of rainfall and maximum and minimum temperature between the two analysis periods. This implies a change in the seasonality and characteristic climate of the region and represents a shift away from the typical climate requirements for maize development. A total of 33,459 km^2 (25% of the total area) of rainfed crops were identified, of which 66.8% experienced changes, mostly in the amplitude of temperature (RCAs 1 to 6). However, 8.8% of the area (RCAs 7 and 8) showed significant changes in all three of the analyzed variables. These changes can be expected to most drastically affect the soil preparation and vegetative growth stages.

These changes in both the magnitude and timing of the climate variables could be problematic given that rainfed production is favored by the long spring-summer cultivation cycle and its associated climate conditions. Overall, the amplitude of temperature increased during this cycle, and higher than usual temperatures were encountered one month before and maintained one month after, which could affect the growth stages of maize. At the same time, a decrease in rainfall was documented, meaning that the water requirements of maize may not be fulfilled.

Additionally, the GDD requirements for different phenological stages of maize were calculated: most RCAs presented changes between the initial and final period, with the GDDs increasing in the final period. This could also affect the suitability of crop areas: certain areas suitable at the beginning of the period may no longer be suitable by the end. In regard to water requirements, few studies have analyzed the amount necessary to promote the vegetative growth of maize, and these have done so in a general manner.

It is hoped that the proposed study opens the door to more in-depth studies on the rainfed cultivation of maize and other crops of interest, including their water and temperature requirements, especially in the RCAs that showed the greatest climate changes. The results can be useful for decision-makers, agricultural planners, and farmers who cultivate rainfed crops during the spring-summer cycle.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

This work was conducted with the support of the Universidad Autónoma del Estado de México and the support of a grant provided by Consejo Nacional de Ciencia y Tecnología (CONACYT).

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