Regional analysis of climate variability at three time scales and its effect on rainfed maize production in the Upper Lerma River Basin, Mexico

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Abstract

This study explored climate variability in the Upper Lerma River Basin, State of Mexico, Mexico, at three timescales: annual (1960 to 2010), monthly (1980 to 2010) and seasonal (1980 to 2010). The effects of monthly and seasonal (2003 to 2010) variability on rainfed maize crops were also evaluated. The variables of rainfall, maximum temperature, minimum temperature and number of hailstorms were interpolated to generate monthly spatial-temporal series. Over a period of 51 years, the climate of the region shows an accumulative annual increase of 131 mm in rainfall and an increase of 0.8 and 0.74 °C in maximum and minimum temperature, respectively. In conclusion, significant changes in the climate variables were found at the three analyzed timescales. Seasonal climate changes were found to coincide with the most vulnerable stage or flowering period of maize; particularly, a shift in the rainfall pattern generates a water deficit that impacts production yield. Hailstorms have increased in frequency, yet their phase shift results in a lesser impact to maize during its most critical stage of development.

Key words: climate variability, Lerma River basin, rainfed maize, seasonal trend analysis, agricultural adaptation

1. Introduction

Agriculture is an important economic, social, and cultural activity, and it is also one of the most determinant factors influencing land uses and transformations across the surface of the Earth. Furthermore, agriculture has contributed towards global warming due to the use of agrochemicals (O'Neill et al., 2005) and the resulting effects of extensive land use changes that lead to modifications of the surface energy and water balance (Foley et al., 2005). The scale and impact of agriculture is evident, where in 2013, farm land for cultivating permanent crops represented 3,400 million hectares or 23 per cent of the world's surface area (FAOstat, 2013).

Although agricultural activity has contributed to climate change, it is in turn affected by changes in rainfall patterns and temperatures, which are key influential factors in agricultural production. In particular, extreme rainfall and temperature events have a negative effect on crop yield (Skoufias and Vinha, 2013), and these may be experienced as more frequent or intense hurricanes, flooding, hailstorms, drought or frosts (Loaiciga et al., 1996; Reyer et al., 2013). Since climate variability affects crop yield in addition to the socio-economic processes involved in the distribution and accessibility of food supplies, the stability of local food systems may be compromised (Ericksen et al., 2009). However, not all of the effects of climate change are easily predictable, quantifiable or able to be absolutely characterized as negative. For example, increasing concentrations of carbon dioxide in the atmosphere could stimulate photosynthesis (Cao and Woodward, 1998), have a fertilizing effect (Florides and Christodoulides, 2009) or improve efficiency of water usage (Keenan et al., 2013), depending on the crop.

While scenarios of climate change may alert to possible social instabilities, within rural communities dominated by traditional means of agriculture, many peasants appear to react satisfactorily to fluctuations in climate (Eakin, 2005; Mortimore and Adams, 2001). Peasants have a varying ability, depending upon their experience, to adapt and respond to climate change. Losses in productivity may be minimized by the use of local, water deficit-tolerant varieties or management systems that employ polycultures, opportune weeding or agroforestry, among other techniques (Altieri and Nicholls, 2009). In fact, peasants have developed agricultural systems over many years to be specifically adapted to local climate conditions, as many are dependent upon subsistence farming and must achieve necessary production levels to satisfy their needs in spite of other disadvantages, such as marginal land holdings, unfavourable topography or climate variability (Andrews and Tommerup, 1995).

At the international level, maize (*Zea mays*) is the third most cultivated crop, after wheat and rice (Asturias, 2004). Maize cultivation originates approximately 7,000 years ago in Mexico and Central America (FAO, 1993). Due to the resistance of maize to variable climate conditions, it was traditionally grown alongside beans and squashes, leading to the emergence of a longstanding agricultural practice that has formed the basis of the Mexican diet. Currently, adaptations to regional climates over the course of thousands of years have resulted in more than 62 documented races of maize in Mexico, including 350 particular varieties that have been conserved on small parcels of land in indigenous and rural communities. Along with its cultural, ritualistic, symbolic, culinary and nutritional uses, maize continues to form the basis of food diet for the majority of the Mexican population (Kato, 2009).

In 2013, according to the Agroalimentary and Fisheries Information Service (SIAP, for its initials in Spanish) of Mexico (SIAP, 2014), 16 million hectares were occupied by rainfed maize crops at the national level, representing 74 per cent of the total area dedicated to maize production. For the same year in the State of Mexico (located in the central portion of the country), 700,000 hectares of rainfed maize were planted, encompassing 84 per cent of state's total maize crops.

In Mexico, extreme climate phenomena regularly affect the agricultural sector. For example (Monterroso et al., 2014) found that from 1980 to 2000 more than 3000 floods, 450 landslides and 750 frosts or hailstorms were reported. Hailstorms are extreme events that have a wide geographical reach and affect five out of every 10 Mexicans, mainly in the northern and central regions of Mexico (Monterroso and Conde, 2015). In this regard, it has been observed that temporal fluctuations in minimum temperature and rainfall coincide with hailstorms, although (Requejo et al., 2012) conclude that regional analyses are important due to the diverse topography and climatology of distinct geographical regions.

Several authors have recognized that in Mexico, rainfed maize crops experience a greater vulnerability to variations in climate (Conde et al., 2006; Eakin, 2005). Variations in temperature, rainfall and hailstorms affect crops differentially, depending on the intensity of the event and their time of occurrence with respect to the phenological stages of the crop. In general, it has been observed that the stages of plant growth and flowering are the most vulnerable to climate events, which may lead to decreases in yield. Thus, the objective of this study was to analyze climate variability and seasonal changes in order to detect spatial-temporal trends in rainfall (*P*), maximum temperature (T_{max}), minimum temperature (T_{min}) and number of hailstorms (*G*) at different time scales and potential effects on the yield of the rainfed maize crops farmed by small-scale peasants in the Upper Lerma River Basin (ULRB) in the State of Mexico. Finally, these analyses are performed with the goal of generating useful information that could aid peasant farmers and improve their capacity to adapt to scenarios of climate variability.

2. Methodology

2.1. Study Area

The Lerma River Basin is located in the central-western region of Mexico and has an area of 54,450 km^2, partially spanning the following five states: Guanajuato, Jalisco, State of Mexico, Michoacán and Querétaro. For the goals of the present study, only the Lerma-State of Mexico subregion was considered, referred to as the Upper Lerma River Basin (ULRB), which corresponds to an area of 5,146 km^2 (Figure 1), and encompassing a total of 27 municipalities and partially intersecting another 15 municipalities (INE, 2006). For subsequent analyses, 32 of the municipalities were considered in order to achieve an overall scenario that would be regionally significant, which included more than 80 per cent of the ULRB territory (10 municipalities were excluded from the analysis because less than 15% of their total area fell within the ULRB). The main hydroclimatological conditions of the watershed are characterized by: (i) an average annual rainfall of 903 mm; (ii) an average annual reference evapotranspiration of 1630 mm; (iii) temperate rainy, semi-cold temperate rainy and cold climates, depending upon altitude; (iv) an average annual temperature of 13ºC and (v) a natural annual run-off of 1,103 hm^3 (Díaz-Delgado et al., 2014). The Upper Lerma River Basin forms part of the Meridional Plateau and experiences periodic droughts, flooding, forest fires, frosts and hailstorms (Gómez and Esquivel, 2002). It is noteworthy that hailstorms coincide with maize crop development (July–October).

2.2. Rainfed Maize Cultivation in the Upper Lerma River Basin

Within the ULRB, maize is the second most produced crop in terms of quantity. This region has the largest number of native maize races at the national level, and several of the following (listed by their names in Spanish) stand out due to their preferential selection by peasant farmers: Cacahuacintle, Cónico, Chalqueño, and Palomero Toluqueño (Romero-Contreras et al., 2006) (Table 1).

These varieties have low photothermal requirements in terms of solar radiation and temperature. This region also has a high level of humidity for an extended period of time, lending to a more or less secure growing season (Gómez and Esquivel, 2002). According to data from SIAP, an average of 210,000 ha of rainfed maize crops are cultivated inside the ULRB. Maize cultivation is significant in this region since its average yield is 4 ton/ha, which is 2 ton/ha higher than the national average (SIAP, 2014).

The standard practice of rainfed maize cultivation revolves around a spring-summer cycle and is the prevalent system used by peasants for subsistence farming. Peasants harvest maize to make quality tortillas, which is a practice that responds to their cultural traditions of food production rather than an exclusively focusing on obtaining high yields (Eakin, 2005; Lerner et al., 2013). Few peasants sell their crop surpluses (Eakin et al., 2014). The initial phase of the production involves a fallow period, followed by the tilling and levelling of the terrain, which usually occurs from January to April. Maize is sown from May to June, depending on the variety, and requires a temperature above 10°C. Approximately 12 kg of seeds/ha are sown, usually at a root depth of 9 cm, although the maximum depth can range up to 46 to 60 cm (Flores and Ruiz, 1998).

The germination phase requires temperatures of 15 to 20 °C. At this stage, plots are weeded during the first 40 days of development in order to avoid competition with weeds. Occasionally, crops are fumigated in the month of June to prevent pests. The first maize cobs begin to appear in August. In September, the maize plants start to dry out. If crops were planted during the first week of May, these are harvested by the end of October. However, periods of harvest also vary according to the variety planted. The grain is usually stored on the cob in a dry and clean hut (troje, in Spanish). The dry stalks, leaves and cobs are an important resource that can be commercialized or used by peasants for other needs (Pérez, 2006).

Maize plants generally follow the same pattern of growth, although the duration of the phenological stages may vary depending on the hybrid, location, season and date of planting. Overall, the growth of maize can be divided into five stages: emergence of plants, vegetative growth, reproductive (flowering and fertilization), development of grains and maturity. In Table 2, the stages of maize growth are summarized overall without specific information on type or variety (Jugenheimer, 1990).

Environmental heterogeneity, geographic isolation and recombination between maize species or neighbouring populations, as well as the selective cropping performed by peasants based on yield or culinary preferences, have all contributed to the diversity and the genetic improvements of many maize varieties and their *in situ* conservation (Eagles and Lothrop, 1994; Vasal et al., 1995). It is notable that indigenous pre-Hispanic populations were the first groups to begin this process of domestication and selective maize cropping, contributing to the rise of this tradition and new varieties of maize.

2.3. Databases for Climate Analysis

The CLImate COMputing project database (CLICOM), managed by the National Water Commission (CONAGUA, for its initials in Spanish) on behalf of the National Meteorological Service (SMN, for its initials in Spanish), contains daily data records from currently and previously active meteorological stations across the country. Data was obtained for 812 meteorological stations located within the region delimited by 18º24’ and 20º52’ N and 101°25’ and 98º35’ W. Based on the recommendation of the World Meteorological Organization (WMO), a minimum period of 30 years was considered, and only data from stations with continuous records of more than 30 years was used. From each station, the averages of the following monthly measurements were calculated: rainfall (*P*), maximum temperature (T_{max}), minimum temperature (T_{min}) and number of hailstorms (*G*). Finally, these averages were interpolated to generate monthly spatial-temporal series at 0.5 km spatial resolution using the distance-weighted average function in the IDRISI Selva software (Eastman, 2012) with a distance weight exponent of two and a search radius of six meteorological stations. This method has been widely use for the interpolation of climate data and has shown good results, as it preserves the values of the sample data and adequately reflect the regional variability in the interpolated series (Vicente Serrano et al., 2003), especially for areas with a high density of climate stations, such as our area of study.

Additionally, a database was used from the Agroalimentary and Fisheries Information Service (SIAP) of the Secretary of Agriculture, Livestock, Rural Development, Fishing and Food (SAGARPA) to obtain relevant data for the study area on rainfed maize production, yield and losses per municipality per agricultural year (2003 to 2010).

2.4. Climate Data Analysis

To determine the effect of climate, one useful technique involves the identification of anomalies in climate variables; these are then compared to the available data on rainfed crop yields in order to consider any potential connections. First, this process consists of defining the base scenario as a function of the average climate behaviour of the region, where in this case, time series were created with the variables of *P*, T_{max}, T_{min} and *G* in order to observe their trends over time. It may be assumed that the interquartile range of the data used to construct the time series represents normal variability. Accordingly, the resulting interquartile behaviour is expected to represent normal conditions of climate variability. For comparison purposes, records of years that show trends in the climate variables outside of their normal range (±2 standard deviations) should be analyzed in greater detail, with the ultimate goal of determining their effect on crop yields.

To achieve this, for the present case study, the water and temperature requirements of maize during different phenological stages were related to climate conditions, in addition to the occurrence of hailstorms and the potential damages to crops (Table 2).

For the analysis of the time series, several statistical techniques from the Earth Trends Modeller (ETM) module in the IDRISI Selva software were utilized (Eastman, 2012) and were applied to achieve the following goals:

(1) To examine the variability in annual time series for climate variables P, T_{max} and T_{min}.

In order to assess the regional annual climate trends for the 1960–2010 period across the arable land area cultivated with maize in the ULRB at elevations of 1900 to 2800 masl (See Figure 1), the non-parametric Theil-Sen test was used (Sen, 1968; Theil, 1950). This test for determines the average gradient of the lineal regressions of P, T_{max} and T_{min} in order to quantify an increase or decrease per unit of time for a given series, as designated by the following equation:

$$\beta = Median\left[x_j - x_i / j - i\right] \qquad for\ all\ i < j \qquad (1)$$

where X_i and X_j represent the values of the time series for years I and j, and β is the magnitude of the gradient.

(2) To observe regional and local monthly trends for *P*, T_{max}, T_{min} and *G* over the 1980–2010 period.

This analysis was performed since recent studies have demonstrated that the effects of climate change has been more pronounced for this period (IPCC, 2014). Equation 1 was calculated again for the given period, in addition to the non-parametric Mann-Kendall test (equations 2, 3, 4 and 5) (Kendall, 1975; Mann, 1945) in order to identify spatial-temporal trends per municipality in *P*, T_{max}, T_{min} and *G*:

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} sgn\left(X_j - X_i\right) \tag{2}$$

$$sgn\left(X_j - X_i\right) = \begin{Bmatrix} +1 \;\; if \;\; \left(X_j - X_i\right) > 0 \\ 0 \;\;\; if \;\; \left(X_j - X_i\right) = 0 \\ -1 \; if \;\; \left(X_j - X_i\right) < 0 \end{Bmatrix} \tag{3}$$

$$Var(S) = 1/8\left[n(n-1)(2n+5) - \sum_{p=1}^{k} t_k\,(t_k - 1)(2t_k + 5)\right] \tag{4}$$

$$Z = \begin{Bmatrix} S - 1/\sqrt{}(Var(S) & if \;\; S > 0 \\ 0 & if \;\; S = 0 \\ S + 1/\sqrt{}(Var(S) & if \;\; S < 0 \end{Bmatrix} \tag{5}$$

where X_i and X_j are the sequences of values of the time series for years *i* and *j*, *n* the longitude of the time series and t_k the number of ties of extent *i*. Finally, to determine if trends were significant, the Kendall's rank correlation coefficient, τ, was used:

$$\tau = S/\,(n(n-1)/2) \tag{6}$$

This indicator has a value ranging from -1 to 1, indicating an increasing or decreasing trend. A value of 1 indicates a trend that continually increases over time and does not fluctuate or diminish, while the opposite, a decreasing trend, is indicated as the value approaches -1. A value of 0 indicates an inconsistent trend (Kendall, 1938).

(3) To determine the local seasonal behaviour of *P*, T_{max}, T_{min} and *G* and compare their coincidence with maize crop losses.

In order to detect seasonal variability, a Seasonal Trend Analysis (STA) was performed (Eastman et al., 2009). This analysis facilitates the evaluation of seasonal trends by using the images of the time series. A harmonic regression is performed according to the following equation:

$$y = \alpha_0 + \sum_{n=1}^{n=2} \{a_n sin(2\pi nt/T) + b_n cos(2\pi nt/T)\} + e \quad (7)$$

where *t* is time, *T* the longitude of the time series, *n* the harmonic (the number of harmonics oscillates between 1 and *T*/2), *e* the term of error and α_0 the average of the series. Finally, by means of a reordination of the terms after calculation, ignoring the rate of error, the seasonal curve can also be expressed by the following:

$$y = \alpha_0 + \sum_{n=1}^{n=2} \propto_n sin\ (2\pi nt/T + \varphi_n) \quad (8)$$

where $\propto_n$ is the amplitude and φ_n the phase angle.

Once the seasonal analysis was completed, the municipalities with the greatest annual crop losses during the 2003–2010 period were identified in order to compare these with changes in *P*, T_{max}, T_{min} and *G* and their incidence during the different phenological stages of maize in order to identify if changes in the seasonality were responsible for crop losses.

3. Results

3.1. Analysis of Annual Climate Variability for 1960–2010

The annual analysis spanned a period of 51 years, taking into account three climate variables: rainfall (*P,* in mm) and minimum and maximum temperature (T_{max} and T_{min}, in °C). The number of hailstorms was not considered since information on their occurrence is not available before 1980. In Figure 2, the results of the yearly profiles are presented along with the Theil-Sen trend line.

In the case of *P*, an anomaly was presented in 1982, representing the lowest level of *P* at 233 mm below the calculated average of 684 mm for the entire study period. Meanwhile, the highest level of *P* occurred in 2010 at 1223 mm, or 306 mm above the annual average. The Theil-Sen trend line shows that the average of *P* in the region has increased from 851 to 982 mm, or by 131 mm, during the last 51 years. The result of the Mann-Kendall statistical test indicated that values for *P* tended towards 1, signifying that within the study area a significant increase in *P* has occurred ($p<0.05$), with an annual average rate of change of up to 2.568 mm per year.

In regards to interannual variation, the lowest average T_{min} was recorded in 1974 at 5.4°C, and the highest average T_{min} occurred in 2010 at 7°C. The time series presented a trend of yearly increase in average T_{min} from 5.76 to 6.50 °C over the course of 51 years, at a rate of change of 0.015°C per year and an overall increase of 0.74 °C. With respect to average T_{max}, 1976 was registered as the coolest year at 20°C, while 2010 was the hottest at 22.6°C, or 1.4°C higher than the overall average of the time series. Similar to *P* and average T_{min}, the T_{max} also presented an increasing trend, as evident in the Theil-Sen trend line, indicating an increase of

0.8°C on average over the course of the last 51 years. The non-parametric Mann-Kendall statistical test was also calculated for T_{min} and T_{max} and tended towards 1 for nearly the entire study area (p<0.05). The variable with greatest significance was T_{max}, presenting a significant increase (p<0.05) in the southern and northern regions within the altitudinal range of 1900–2800 masl. Since 1980, an increasing trend exists for all three climate variables, which is in agreement with IPCC reports (IPCC, 2014) that identify similar increases and attribute these mainly to the rise in fossil fuel consumption. This fact prompted a more detailed analysis of the climate variables from 1980–2010 to examine monthly trends.

3.2. Analysis of Monthly Climate Variability for 1980-2010

Extreme variations in the monthly behaviour of the climate variables within the study area were found and appear to be associated with the climatic phenomena of El Niño and La Niña, as observed in Figure 3.

Worldwide, the most documented El Niño events in terms of intensity and magnitude correspond to the episodes of 1982-1983 and 1997-1998 (Timmermann et al., 1999), which had severe socioeconomic impacts and affected vulnerable populations and numerous other sectors. The relationship of these events with the analysed climate variables may be observed in the temporal climate profiles (Figure 3). With respect to losses in maize production, after 2004 the records are expressed in terms of percentages.

The occurrence of extreme events corresponds with the lines that lie furthest from the average trend lines of the series. In 1982 and 1983, the lowest P values may be observed, with a low of -90 mm for September 1982. Meanwhile, the T_{max}

occurred in May 1983, which was the second highest temperature recorded for the entire 51-year period, or 2.25 °C higher than the average T_{max} for the month of May. However, the greatest anomalies were observed for 1997 and 1998, corresponding with the El Niño event of greatest recorded impact worldwide. The highest peak in T_{max} anomalies is presented in May 1998, at 3°C higher than the average temperature for this same year, in addition to the highest level of P at 150 mm.

In comparing the monthly trends of the climate variables with data from SIAP on damaged crops, in 2005 almost 20 per cent of the harvested area of the ULRB was lost. This year corresponds with the El Niño phenomena and also the second driest April recorded at the national level since 1941 (CONAGUA, 2005). During this same year, due to drought, the Secretary of Agriculture, Livestock, Rural Development, Fisheries and Food (SAGARPA, for its initials in Spanish) launched a Contingent Climate Declaration in order to guide the operation of the Fund for Attending to Rural Populations Affected by Climate Contingencies (FAPRACC, for its initials in Spanish) in several municipalities of the State of Mexico (DOF, 2005).

Furthermore, in Figure 4 the results for coefficient τ from Kendall's rank correlation may be observed, and it is notable that the trend values for all variables, whether positive or negative, were significant ($p<0.05$) for the area of study. In this figure, T_{max}, and T_{min} are observed to have similar behaviour in the ULRB, demonstrating an increasing trend over time. The number of hailstorms (G) has tended to increase in the south-western portion of the study area and decrease in the north-western municipalities. This behaviour could be favourable for seasonal cropping, given that the municipalities where G have diminished also have a greater arable crop area. *P* has also tended to increase in the majority of municipalities within the study area, with the exception of Temascalcingo, Acambay, El Oro, San José del Rincón, and San Felipe del Progreso, located in the north-western portion of the study area. It is important to point out that although rainfall levels have been increasing in the majority of municipalities, this is not necessarily favourable for rainfed maize crops, as their success depends not only on quantity of rain but also the presence of rain during critical stages of growth. In light of this scenario, an additional seasonal analysis was carried out to establish if these changes have been beneficial or detrimental to peasants.

3.3 Seasonal Analysis

The final portion of the analysis had the goal of detecting possible seasonal trends in the climate variables and their effect on the development and production of maize during different phenological stages, which have varying climate and temperature requirements. First, seasonal curves were modelled for each year, and then trends in variability were compared with the regional annual averages. Images were generated to display the slope of the amplitudes for the stages, including superimposed trend lines to facilitate comparison between seasons. For this type of analysis, Eastman (2009) recommends that 15–25 per cent of the extreme absolute values (both positive and negative) be used for comparison. For this reason, a period of 7 years was selected at the beginning and end of the time series, representing the extreme values of the analysis period.

The differences in the monthly averages at the beginning and end of the study period (Figure 5, solid lines) show a scenario of climate variability that could directly influence maize production. A phase change is observed in peak rainfall, shifting from the month of August to September. A difference in amplitude is also evident, corresponding to a *P* increase of nearly 50 mm. A similar behaviour is observed for hailstorms, where a slight phase shift and increase in amplitude lead to a higher frequency and intensity of storms during July and August.

The T_{max} also shows a significant change, although more in amplitude than in phase shift. An increase of approximately 1°C throughout the year is observed, with the exception of November and December.

In Figure 5, the potential effects of climate variations on each of the phenological stages of maize can be visualized. Undoubtedly, the most critical stage occurs three weeks before flowering, as a sufficient water supply is necessary for development. A *P* level of approximately 300 mm from May to September is ideal, and half of this *P* should occur from June to August (Llanos, 1984). In the 1980-1987 period a greater number of *G* occurred in July, showing the occurrence of a phase change in comparison to the 2003–2010 period, when more *G* occurred in August after the end of the flowering stage. In this sense, the probability of *G* damaging maize plants due to defoliation actually decreases.

Temperature and its fluctuation also greatly influence maize plants during their development. During the emergence stage, maximum daily fluctuations in ambient temperature should not exceed ± 7°C. The isothermal limit for maize cultivation is 18 °C, while the optimal temperature is 22 °C. However, high temperatures at the end of July and August could wilt leaf tissues or cause low production of grains. In addition, a marked decrease in air or ground temperature, especially towards the end of the development cycle, delays the maturation of the grains. Finally, increases in humidity may also have adverse effects and foster diseases. Yet overall, dry periods of higher than average temperatures result in lower maize yields, especially when these conditions are experienced during the flowering stage.

Finally, to exemplify the effects of the seasonal variability of P, T_{max}, T_{min} and G on maize crops, a case study of the municipality of Almoloya del Juárez is presented (Figure 5, dashed lines). For this analysis, annual data for one year with an extensive crop loss area (2005) and for another year without crop loss (2007) were compared. For 2005, a surface area of 20,747 ha of rainfed maize was cultivated, and 9,564 ha were reported as damaged, demonstrating direct and negative repercussions due to climate (Figure 5, bars graph). According to the North American drought monitor of the National Meteorological Service of Mexico (SMN, for its initials in Spanish), the month of April 2005 was reported as the second driest at the national level since 1941 (CONAGUA, 2005). On the other hand, in the following month of May, rainfall was geographically concentrated in the northern regions of the country, negatively impacting the initial stages of the growing season for the study area. The rainy season also presented a delay of three to four weeks, and consequently, maize production for that year was reported as severely damaged by the local government, with the State of Mexico being the most affected nationwide.

Essentially, in 2005 the hydric conditions necessary for the emergence and vegetative growth stages of maize were absent, and expected production levels were not met. Additionally, the T_{max} was higher with two significant peaks in May and July, although low T_{min} had also been registered in April in addition to several atypical *G*. In comparison, humidity conditions in 2007 were favourable during the entire agricultural cycle. The greatest number of *G* occurred in July and September, although this did not appear to affect maize yields. Therefore, it may be proposed that for the maize varieties cultivated in the study area, production is mainly affected by seasonal fluctuations in *P*, as demonstrated in 2005.

4. Conclusions

The annual, monthly and seasonal analyses of rainfall, number of hailstorms and minimum and maximum temperatures in the Upper Lerma River Basin at elevations of 1900 to 2800 masl allowed for the visualization of regional climate variability in order to assess its effects on the production of rainfed maize. As observed along a yearly timescale, maximum and minimum temperatures tended to increase, following global trends, and interannual variability in temperature and rainfall was highly influenced by El Niño and La Niña events. However, at a monthly timeframe, these events do not predictably influence climate variables but rather vary in duration and intensity. This is observed for the El Niño events of 1982-1983, 1997-1998 and 2005, where the last event damaged 20 per cent of the area cultivated with rainfed maize, as reported by SIAP. Spatially, the maximum temperature, minimum temperature and rainfall levels have tended to increase throughout the larger portion of the arable area of the Upper Lerma River Basin, while in contrast, hailstorms have tended to decrease, overall.

According to the seasonal analysis, the monthly averages for maximum and minimum temperatures have tended to uniformly increase over the course of the time series. Rainfall has also tended to increase and has been increasingly concentrated in the June–September period, although it was previously more uniformly distributed throughout the May–September period. In comparing these changes with the phenological stages of maize, the hydric and thermal requirements of plants may no longer be fulfilled during critical stages of development. However, in spite of severe climate events, the Agroalimentary and Fisheries Information Service (SIAP) has reported that, overall, production levels in recent years have not been significantly affected. This may be attributed to the ability of peasants to adapt to changing circumstances.

Finally, it may be highlighted that in Mexico and in particular for the study area, greater government investment and more in-depth research are required to explore possible means of adaptation that would assist local peasants facing climate variability and change. Empirical observations have confirmed that peasants in the study region are equipped with extensive knowledge and a series of farming practices that may be reinforced with scientific knowledge, therefore increasing the viability of crops under scenarios of climate change. In addition to adaptation measures, a successful and consistent maize production is also dependent on the functioning of the greater social-agricultural-economic system, which given its complexity, requires interdisciplinary studies to evaluate in greater depth the indirect effects of climate variability and change. Furthermore, other interconnected climate, social or environmental changes may also affect populations.

Additional studies are also recommended for building climate prediction models in the medium-term that would allow for the ideal vegetative cycles to be anticipated. In this scenario, recommendations may be made on where and when to plant certain maize varieties. Such an objective would not only on highlight the necessary conditions for obtaining a good harvest, but would also involve a reframing of social values pertaining to rural agriculture. In this sense, the goals of safekeeping agricultural knowledge and practices and the promotion of custodianship must be prioritized in order to conserve the genetic biodiversity of native maize. Such goals would ultimately contribute towards food sovereignty. The dissemination of this knowledge at a larger scale, given the unfortunate occurrence of extreme climate events and their negative consequences for peasants, can be framed as an additional component of the Agrarian Question (Akram-Lodhi and Kay, 2010a, 2010b), which has re-emerged at the beginning of this century and is defined by the persistence of peasants and practices concerning seasonal and rainfed crops despite lack of support or the intervention of public policies.

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Figure captions

Figure 1. Location of the Upper Lerma River Basin (ULRB) and the 32 municipalities that compose more than 80 per cent of the study area (1900–2800 masl)

Figure 2. Annual trends for average rainfall (a), minimum and maximum temperatures (b) for the 1960–2010 period in the ULRB (1900–2800 masl). β =slope

Figure 3. Seasonal variability and percentage of damaged maize crop area for municipalities located in the ULRB (1900–2800 masl).

Figure 4. Kendall's rank correlation coefficient, τ, for rainfall, number of hailstorms and minimum and maximum temperature (no trend if τ=0, trend if τ >0 or τ <0 [p<0.05]).

Figure 5. Seasonal analysis for rainfall, number of hailstorms and minimum and maximum temperature in the ULRB (1900 to 2800 masl) (solid lines). The numbers correspond to the cultivation and phenological stages of maize; 1: preparation of the field, 2: sowing, 3: emergence, 4: vegetative growth, 5: flowering, 6: fertility, 7: growth of grains and maturity and 8: harvest.

Table Captions

Table 1. General characteristics of the principal maize varieties planted in the State of Mexico.

Table 2. Stages of maize (*Zea mays*) growth, considering variations in development time for different varieties. Source: (Jugenheimer, 1990).

Table1

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Type	Elevation (masl)	Characteristics	Location
Palomero toluqueño	2200-2800	Utilized mainly for re-planting when seeds have been lost due to environmental damages or pests. Resistant to cold, drought, and pests. Early maturation (Romero-Contreras et al. 2006). Useful for developing genotypes of early-maturing varieties of rainfed maize (González Huerta et al. 2007). Characterized by the small dimensions of its cob and grain. Used to obtain oil and for bird and livestock feed and popcorn (Wellhausen et al. 1951).	Toluca and Atlacomulco
Cacahuacintle	2200-2800	Varying yield from 2.5 to 6.5 ton/ha (Domínguez López et al. 2006). Dependent on a semi-cold microclimate, high altitude, and well-filtered soils. Susceptible to root lodging and Fusarium ear rot (González Huerta et al. 2007).	Calimaya, Toluca, Atlacomulco, Capultitlán, Metepec, San Mateo Atenco, and Tenango del Valle (González Huerta et al. 2007)
Cónico	2200-2800	Great tolerance to root lodging and ear rot. High yield. Useful for developing genotypes of early-maturing varieties of rainfed maize (González Huerta et al. 2007).	Ixtlahuaca and Metepec. High valleys of the central mesa.
Chalqueño	1900-2300	Diverse coloured grains: white, cream, yellow, red, blue, or black. Tolerant to drought and low temperature. Susceptible to frosts. Vegetative period of 5 to 6 months. High yield.	High central valleys of Mexico.

Table2

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Stages	**No. Days**	**No. Days Accumulated**	**Characteristics**
Emergence	9	9	Coleoptile breaks through the soil.
Vegetative growth	49	55	Development of leaves and longitudinal growth of main stalk. Forms the most important period for the plant and subsequently influences the harvest. Most critical point occurs three weeks prior to flowering.
Reproductive	14	69	Male flowers and pollen produced. Presence of visible stigma.
Development of grains	11	80	Grains begin to reach final size.
Maturity-senescence	15	95	Hard and shiny grains. Stalks begin to break.

Figure1
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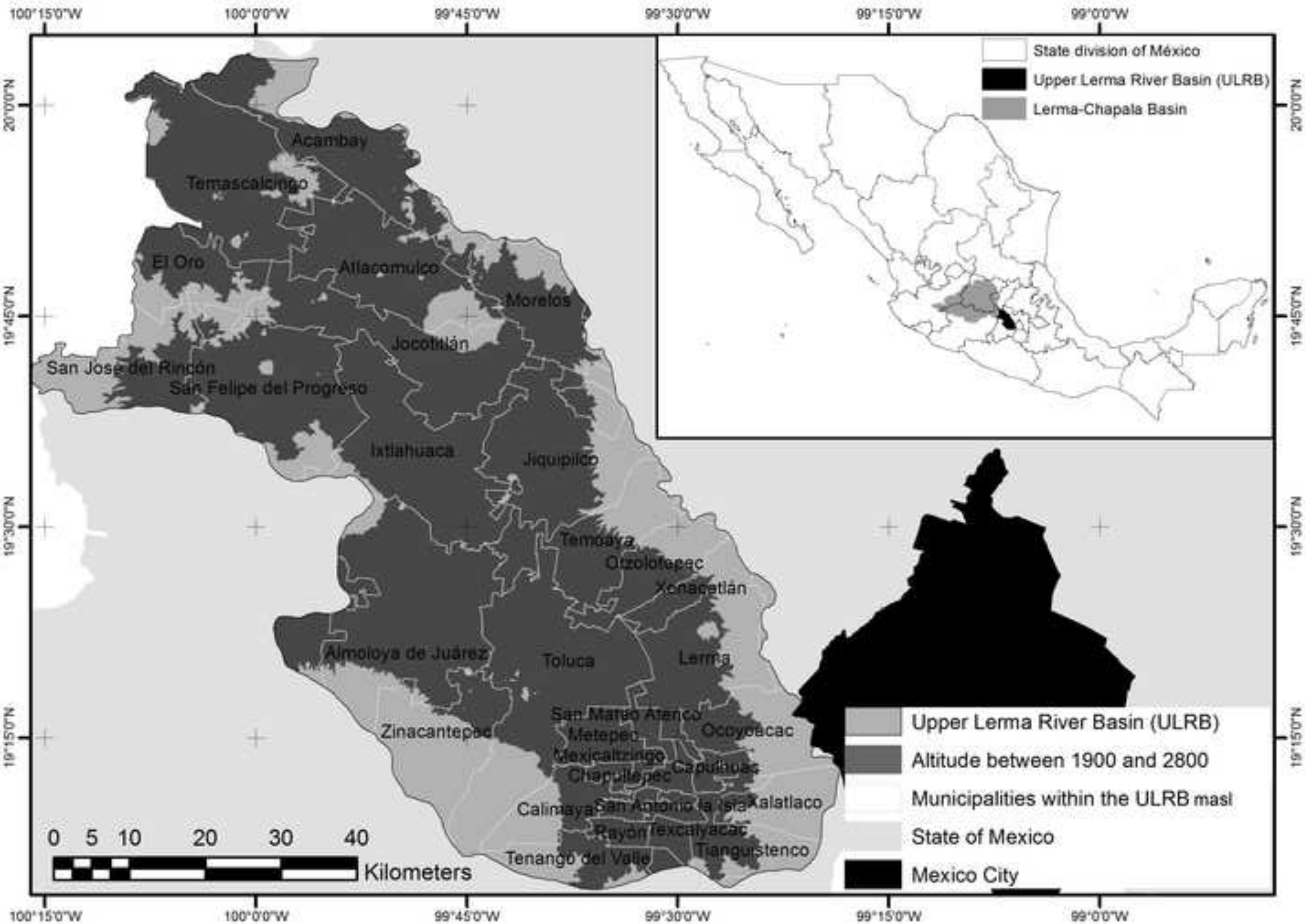

Figure2

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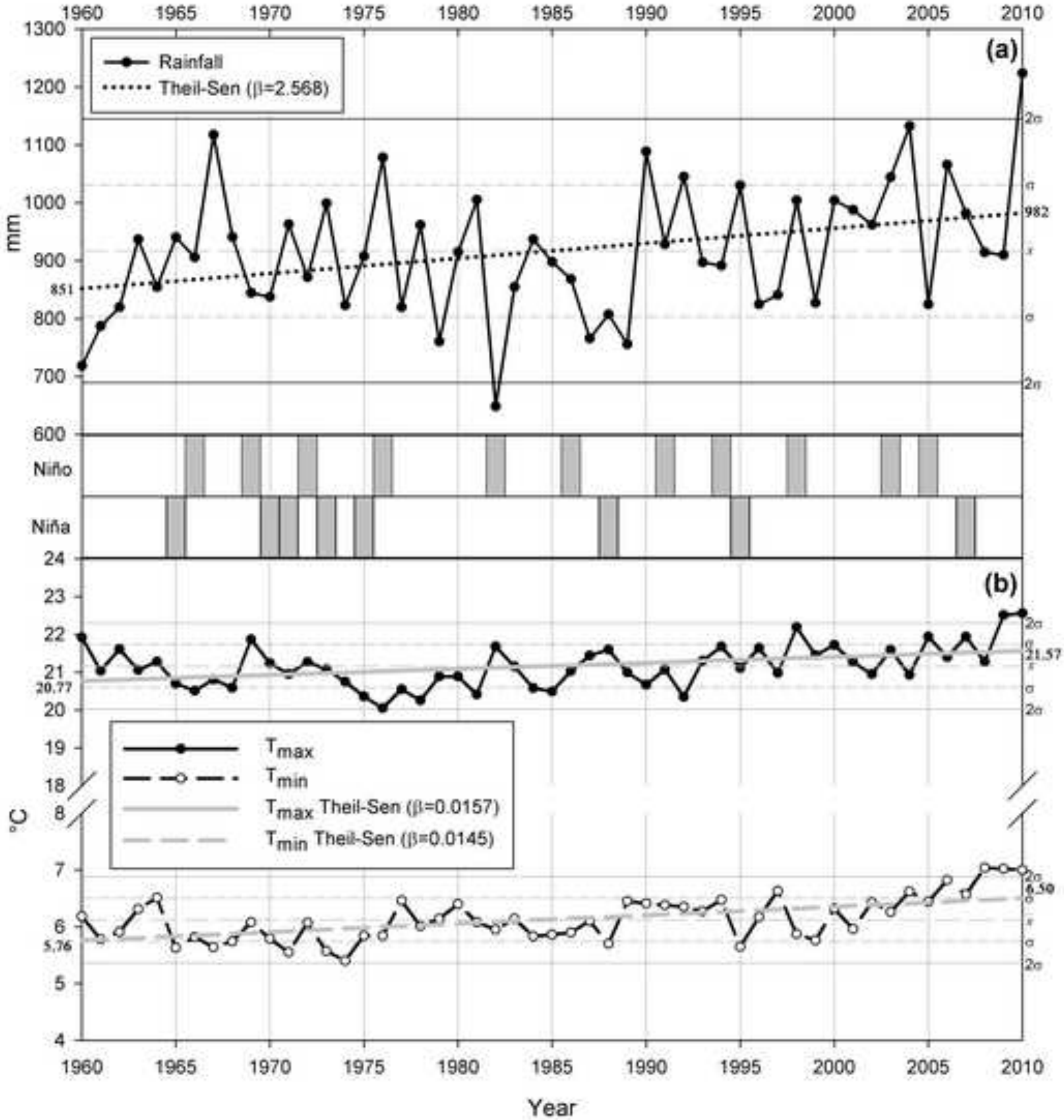

Figure3
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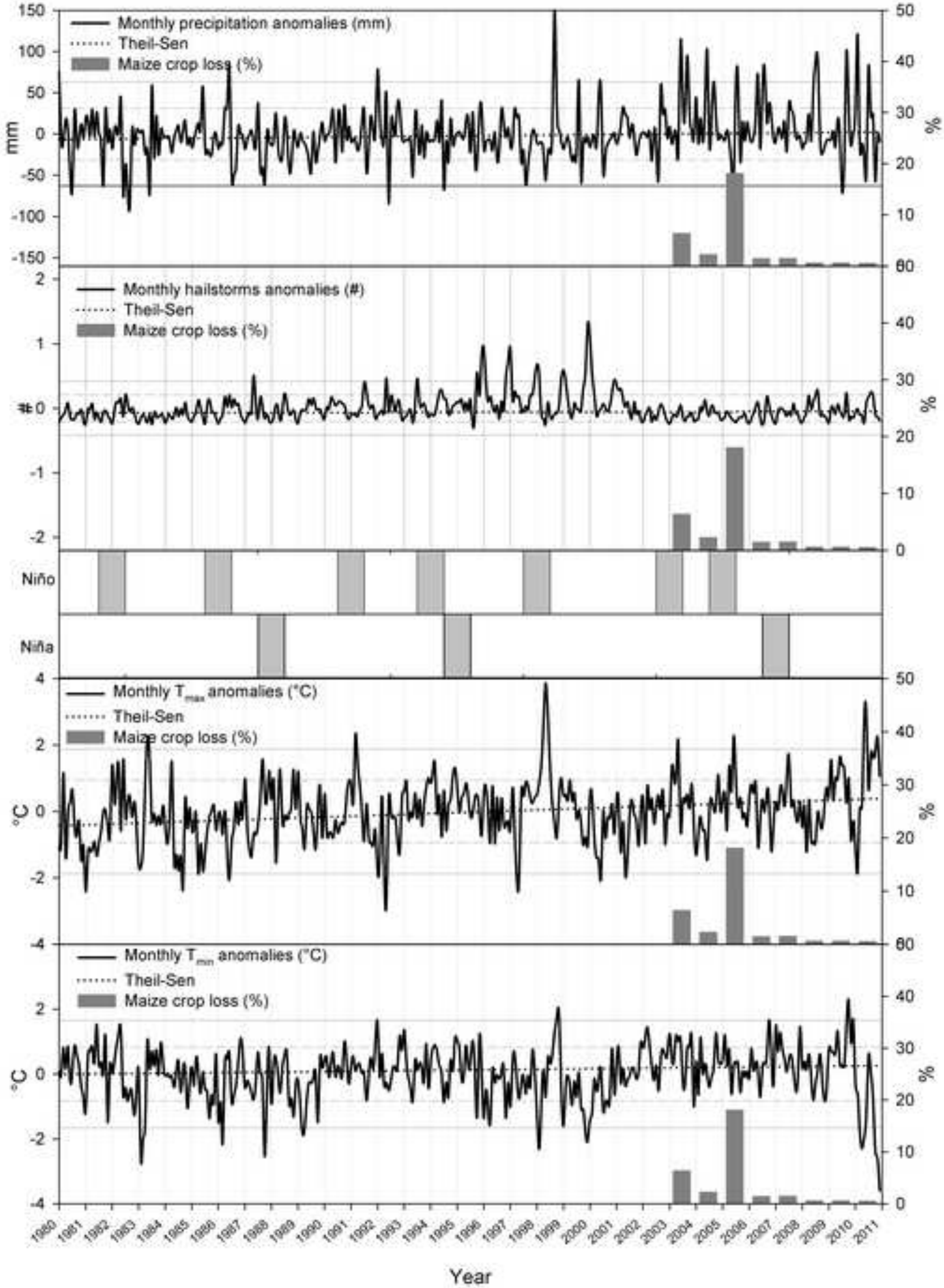

Figure4

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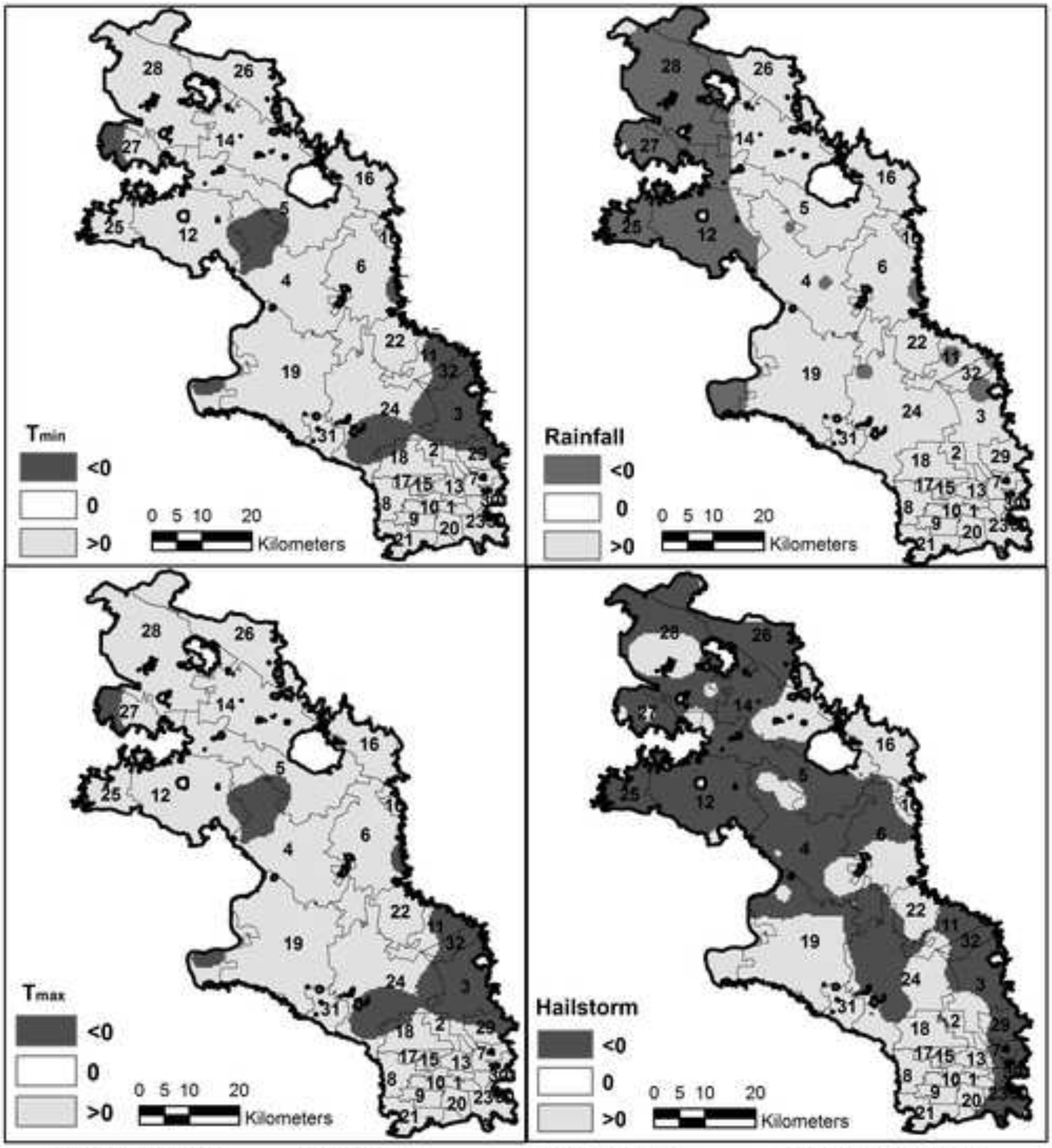

1 Almoloya del Río
2 San Mateo Atenco
3 Lerma
4 Ixtlahuaca
5 Jocotitlán
6 Jiquipilco
7 Capulhuac
8 Calimaya
9 Rayón
10 San Antonio la Isla
11 Otzolotepec
12 San Felipe del Progreso
13 Atizapán
14 Atlacomulco
15 Chapultepec
16 Morelos
17 Mexicaltzingo
18 Metepec
19 Almoloya de Juárez
20 Texcalyacac
21 Tenango del Valle
22 Temoaya
23 Tianguistenco
24 Toluca
25 San José del Rincón
26 Acambay
27 El Oro
28 Temascalcingo
29 Ocoyoacac
30 Xalatlaco
31 Zinacantepec
32 Xonacatlán

Figure5

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