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Articles

The global climate change footprint in a Mexican desert ecosystem: The increasing frequency of extreme climatic events

Huella de cambio climático global en un ecosistema desértico de México: aumento de frecuencia de eventos climáticos extremos

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Abstract

While the accuracy of scenarios of Global Climate Change has been improved, the lack of climatic data from several regions of the world means that some predictions remain misleading. The local climate studies are critical for the calibration of global climate scenarios. Our objective was to evaluate the climate trends within the Cuatro Ciénegas Basin (CCB). Specifically, we aimed to: 1) identify potential trends in the behavior of temperature and precipitation; 2) assess the nature and direction of changes in the frequency of extreme climate events (ECE); and 3) detect changes in inter-annual precipitation variability. To achieve these aims, we analyzed a 70-year database of climatic variables from the CCB weather station. Data were subjected to trend analyses using two different software packages; ECE frequency was evaluated by Chi-square analysis and precipitation data was analyzed by the standardized pluviometric drought index Minimum temperature (T_{min}) increased in almost 2 °C every month, while mean temperature (T_{mean}) increased 2 °C but only in the summer months. Lower T_{min} frequency increased two times or higher in the winter months, while the frequency of upper event extremes increased at least three times during the summer months, as did the extreme events of maximum temperature (T_{max}). Winters have therefore become colder while summers have become warmer, increasing the frequency of heat waves over the last 36 years. However, monthly precipitation patterns presented high variability that obscured any trend in the ECE of precipitation events. Over the last 36 years, frequencies of events of both intense precipitations associated with tropical cyclones and intense drought associated with the ENSO were higher than before.

Keywords: Climate trends, Chihuahuan desert, extreme climate events, precipitation, temperature.

Resumen

Si bien se ha mejorado la precisión de los escenarios del cambio climático global, la falta de datos climáticos de varias regiones del mundo significa que algunas predicciones presentan gran incertidumbre. Los estudios climáticos locales son críticos para la calibración de escenarios climáticos globales. El objetivo fue evaluar tendencias climáticas dentro de la cuenca de Cuatro Ciénegas (CCB). Específicamente: 1) identificar tendencias potenciales en el comportamiento de la temperatura y la precipitación; 2) evaluar la naturaleza y dirección de los cambios en la frecuencia de eventos climáticos extremos (ECE), y 3) detectar cambios en la variabilidad interanual de la lluvia. Para lograr estos objetivos se analizó una base de datos de 70 años de variables climáticas de la estación meteorológica CCB. Los datos se sometieron a análisis de tendencias utilizando dos paquetes de *software* diferentes; la frecuencia ECE se evaluó mediante análisis de Chi-cuadrado y los datos de lluvia se analizaron usando el índice pluviométrico estandarizado de sequía. La temperatura mínima (T_{min}) aumentó al menos 2 °C en casi todos los meses y la temperatura media (T_{mean}) subió 2 °C, pero sólo en meses de verano. En los ECE los inviernos se han vuelto más fríos, mientras que los veranos se han vuelto más cálidos; se incrementó la frecuencia de las olas de calor en los últimos 36 años. Sin embargo, los patrones mensuales de lluvia presentaron una gran variabilidad que oscureció cualquier tendencia en la frecuencia de ECE de lluvia. En los últimos 36 años, las frecuencias de eventos de lluvias intensas asociadas con ciclones tropicales y sequías intensas han aumentado.

Palabras clave: tendencias climáticas, desierto chihuahuense, eventos climáticos extremos, precipitación, temperatura.

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Introduction

Global Climate Change (GCC) affects both the components and functioning of ecosystems (IPCC, 2013; Rustad, 2008). According to the IPCC, the globally averaged combined land and ocean surface temperature data as calculated by a linear trend, shows a warming of 0.85 °C, over the period from 1880 to 2012, but global changes in precipitation show no clear trend (IPCC, 2013). Similarly, heat waves have increased in intensity since the mid-20th century in the majority of world regions, but the temporal pattern of torrential rains and drought remains unclear at global level (IPCC, 2013). This lack of a clear pattern in the trends of precipitation events is explained by the absence of long-term precipitation data for several regions of the planet and also because precipitation patterns depend mainly on regional phenomena, which are not reflected in global models (Archer & Predick, 2008; Easterling *et al*., 2000; Grimes & Pardo-Igúzquiza, 2010). Precipitation variability complicates the accurate assessment of contemporary precipitation distribution trends and the potential impacts of GCC (Batisani & Yarnal, 2010). This lack of data is particularly critical in arid and semiarid regions, especially in Latin American desert ecosystems (IPCC, 2013).

According to the World Atlas of Desertification (UNEP, 1992), drylands have a ratio of average annual precipitation (P) to potential evapotranspiration (PET) of less than 0.65, which produces a water deficit stress for plants and animals. The quantity of precipitation and ambient temperature are both important factors in determining the amount of water available for primary productivity and for the biological activity of organisms (Holmgren *et al*., 2006; Williams, 2014). Inter-annual climatic variability in these ecosystems determines the occurrence, duration and intensity of flood and drought conditions (D'Odorico, Bhattachan, Davis, Ravi, & Runyan, 2013; Jun, Dunxian, Yongyong, & Hong, 2012). However, variability in annual levels of precipitation could be increased by GCC over

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the 21st century (Jain & Kumar, 2012).This variability is a consequence the increasing frequency and intensity of extreme climate events (ECE) (D'Odorico & Bhattachan, 2012; IPCC, 2012). An ECE is defined as the occurrence of a value of climate variable with very low probably of occurrence (IPCC, 2012). These events are completely stochastic and can alter, sometimes irreversibly, the structure and functioning of ecosystems (Jentsch & Beierkuhnlein, 2008). Some predicted scenarios for the inter-annual variability in desert precipitation include: decreased variability in Africa (Namib desert) and Australia (Tanami, Simpson and Stzelecki deserts), and increased variability in India (Thar desert), as well as an increase then decrease in the USA (Mojave desert) and Botswana (Kalahari desert) (Archer & Predick, 2008; D'Odorico & Bhattachan, 2012).

Desert ecosystem vulnerability is defined as its susceptibility to disturbances such as those produced by GCC or ECE (D'Odorico *et al*., 2013; IPCC, 2013). In this ecosystem, vulnerability is governed by: 1) the character, magnitude and rate of a disturbance to which an ecosystem is exposed, and 2) the sensitivity and adaptability of the ecosystem to that disturbance (IPCC, 2012). Desert ecosystems are considered extremely vulnerable to GCC, particularly ECE, because the plants and animals in these systems live near to their physiological limits in terms of water and temperature requirements, and can therefore be very sensitive to even moderate changes in climate (Archer & Predick, 2008; Lioubimtseva & Henebry, 2009). For this reason, it has been proposed that failure to mitigate the GCC will lead to an increased frequency and severity of ECE in the future, which could have negative and irreversible

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impacts on the functioning of desert ecosystems (Jentsch & Beierkuhnlein, 2008; Reichstein *et al*., 2013).

The scenarios for the Sonoran and the Chihuahuan deserts in Mexico include decreased annual precipitation and, an increased number and intensity of individual precipitation events, accompanied by rising mean annual temperatures (Archer & Predick, 2008; Bell *et al*., 2014; Loarie *et al*., 2009). In addition, the ECE projections imply lower frost frequencies and higher frequencies of heat waves, droughts, storms and floods (IPCC, 2013).The Chihuahuan desert has been classified as one of Earth's most biologically outstanding habitats by the World Wildlife Fund (Archer & Predick, 2008). The Cuatro Ciénegas Basin (CCB),which is the study site of the present paper, is located in the Chihuahuan desert and is considered the most important wetland of Mexico because of its high levels of endemism and biodiversity (Souza, Siefert, Escalante, Elser, & Eguiarte, 2011). However, the alfalfa fields that represent the main agricultural crop within the CCB demand great quantities of water and the practice of irrigation is mainly done by flood irrigation, which promotes soil degradation and biodiversity loss (Hernández-Becerra *et al*., 2016).

Climate change scenarios are commonly constructed based on Atmosphere Ocean Global Climate Models (AOGCMs) (IPCC, 2013); however, these models do not take local climate dynamics into account, and their use therefore increases the uncertainty of projected scenarios at this scale. The integration of other analytical tools is therefore required for climatic trends at regional and local scales (Jun *et al*., 2012; Tabari & Hosseinzadeh-Talaee, 2011). Among these tools, trend analyses of time series (Bautista, Bautista-Hernández, Álvarez, Anaya-Romero, & De-la-

Rosa, 2013; Jain & Kumar, 2012) and analyses of ECE frequency can be of particular value (Easterling *et al*., 2000).

The objective of the present study was therefore to evaluate the effect of GCC in the CCB over the last 70 years (1941 to 2013). Specifically, we aimed to: 1) identify trends in the behavior of climatic variables (temperature and precipitation); 2) assess the nature and direction of changes in the frequency of ECE; and 3) detect changes in inter-annual variability of precipitation throughout the year over the last 70 years. We hypothesize increases in atmospheric temperature, frequency of ECE and precipitation variability. To test these hypotheses, we analyzed a 70-year database of climate variables from the CCB weather station.

Materials and methods

Study site

The study was carried out in the Cuatro Ciénegas Basin (CCB; 26° 45’- 27° 00’ N and 101° 48’- 102° 17’ W) in central-northern Mexico, which is part of the Chihuahuan Desert (Figure 1). The CCB has an area of 150,000 km^2, the study area had an elevation of 740 masl and it is completely surrounded by mountains. These geographical barriers are favored that the climate dynamic differentiated from the rest of the Chihuahuan Desert (Archer & Predick, 2008). The climate is seasonally arid with two contrasting seasons and an average annual temperature of 21.2 °C with 252.5 mm of annual precipitation (SMN-Conagua, 2018). The first season, from November to April, is cold and dry with minimum and maximum temperatures of 4.8 and 29.8 °C, respectively, and 65.9 mm of precipitation. The second season, from May to October, is hot (with minimum and maximum temperatures of 15.7 and 33.4 °C, respectively) and around 60 % (186.6 mm) of the total annual precipitation is concentrated within this season (SMN-Conagua, 2018). Jurassic-era gypsum is the dominant parent material at the western side of the basin, while Jurassic-era limestones dominate the eastern side (McKee, Jones, & Long, 1990). According to the World Reference Base for soil resources (WRB, 2015) the predominant soils are *Gypsisol* and *Calcisol* at the western and eastern sides of the basin, respectively. The main vegetation types are: 1) grassland (G), dominated by *Sporobolus airoides* (Torr.) Torr., and *Allenrolfea occidentalis* (S. Watson) Kuntze; 2) microphyll scrub, dominated by *Jatropha dioica* Cerv., *Larrea tridentata* (DC) Cov., and *Fouqueria sp* Kunth (Perroni, García-Oliva, & Souza, 2014); and 3) rosetophylous scrub (RS) dominated by *Dhasylirium cedrosanum* Trel., and *Yucca treculeana* Carriére (González, 2012).

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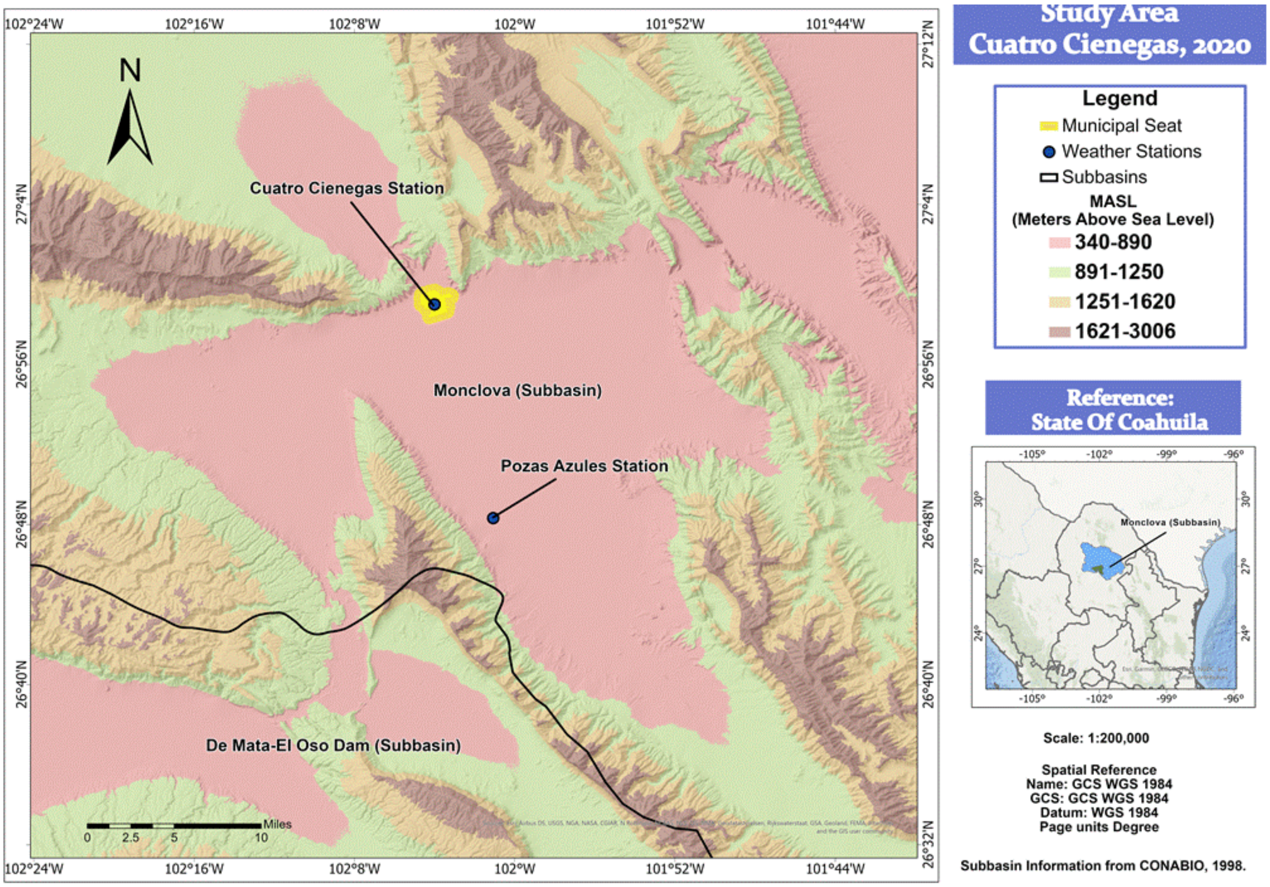

Figure 1. Location of the Cuatro Ciénegas Basin (CCB) in Coahuila, Mexico.

Climate data set

For the present study, a data set covering a 70-year period (1941 to 2013) was analyzed. The data came from two weather stations within CCB (Cuatro Ciénegas station of the Mexican National Water Commission (http://smn.cna.gob.mx/, data from 1941 to 2013) and the "Rancho Pozas Azules" station of INIFAP (http://clima.inifap.gob.mx/redinifap/, data from 2005 to 2013; Figure 1). Daily and monthly data were used to evaluate the following parameters: precipitation (pp), mean temperature (T_{mean}), maximum temperature (T_{max}) and minimum temperature (T_{min}). The pp, T_{max} and T_{min} databases were subjected to quality control in order to identify possible errors (i.e., pp > 0 or $T_{min} > T_{max}$; (Moberg & Jones, 2005). The monthly thermal oscillation was calculated from the difference between T_{max} and T_{min} (Tabari & Hosseinzadeh-Talaee, 2011).

Trend analysis: temperature and precipitation

EViews version 7.0 (Quantitative Micro Software) for parametric statistics (López-Díaz, Conde, & Sánchez, 2013) and Clic-MD version 2 for nonparametric statistics (Bautista *et al*., 2013) were used for analyzing temporal trends in temperature and precipitation. For the EViews model, the following assumptions were tested before performing the trend analysis: normality, functional form, no autocorrelation, correct specification, structural permanence, multicollinearity and no

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homoscedasticity. To test if the slope of the relationship between the climate variable and time differed from zero, EViews adjusted this relationship to a least squares linear regression model (López-Díaz *et al*., 2013):

$$y = C\ a_j x_j + e \quad for\ j = 1 \dots n \tag{1}$$

Where "y" is the climate variable (temperature or precipitation), x_j the time, C a constant coefficient, a_j the regression parameter (slope), and e the residual error. An increase or decrease of the trend for the climate variable under analysis was indicated by a positive or negative "a" value, respectively. Slope intensity was analyzed by Pearson correlation analysis (López-Díaz *et al*., 2013).

The Clic-MD software (Bautista, Pacheco, & Bautista-Hernández, 2014) included two statistical analyses: 1) a Spearman simple linear correlation was used to evaluate changes in climate variable intensities, and 2) a non-parametric Mann-Kendall test (MK-T) was used for analysis of the temporal trends of climatic variables (Jain & Kumar, 2012). The MK-T tests the null hypothesis of no temporal trend (where the slope is equal to zero; (Tabari & Hosseinzadeh-Talaee, 2011). The null hypothesis is rejected when Z > 1.96. Positive or negative values of Z indicate increments or decrements of the climate variable in the time series, respectively (Bautista *et al*., 2013; Jun *et al*., 2012). The autocorrelation of the residuals was analyzed by the Breusch-Godfrey test (Breusch,

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1979). Additionally, the homoscedasticity was analyzed by the White test (Bautista *et al*., 2014).

Analyses of Extreme Climate Events (ECE)

The ECEs were identified as those values below the 10^{th} (lower extremes) or above the 90^{th} (upper extremes) percentile distribution values in any climate parameter (Ben-Gai, Bitan, Manes, Alpert, & Rubin, 1999; Easterling *et al*., 2000; IPCC, 2012). For this analysis, we used daily temperature data and monthly precipitation data. In order to analyze whether the frequency of temperature (T_{max} and T_{min}) and precipitation ECEs had changed over the last 36 years, the 70-year CCB dataset was divided into two time periods: a) from 1941 to 1976 and b) from 1977 to 2013. The series of 70 years was split in two to ensure that each period had at least 30 years of data according to the number of years needed to define a climate (WMO, 2018). A chi-square test was used to identify changes in the frequency of lower and upper extreme events of T_{max}, T_{min} and for upper extreme events of precipitation between the two time periods. To identify monthly changes between the two time periods, we applied a residual analysis to the lower and upper extreme events of T_{max}, T_{min} and precipitation. Where the residual value was > 1.96 or < -1.96, the change in frequency was considered to be significant (Ben-Gai *et al*., 1999; Everitt, 1992).

Precipitation analyses

We used a data set of 70 years (1941 to 2013) for calculated an index based on rainfall data: the standardized pluviometric drought index or SPDI (Pita, 2001; Thielen *et al*., 2020). The SPDI is an index based on cumulative monthly precipitation anomalies and is used to identify the duration and the severity of both, drought (Alexander *et al*., 2006; Thielen *et al*., 2020) and humidity (Thielen *et al*., 2020). For the SPDI calculation, the equation used was:

$$SPDI = (APA_i - \overline{APA})/\sigma APA \qquad (2)$$

Where the APA_i is the accumulated rainfall anomaly for month i. The $\overline{APA}$ is the average value of the accumulated precipitation anomalies of all the months in the data series. The σAPA is the standard deviation of the accumulated precipitation anomalies of all the months in the series (Thielen *et al*., 2020).

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The indexes for the 70 years were calculated and graphed with the software CLIC-MD version 2 (Bautista *et al*., 2013). The indexes values obtained from each month were classified into a category according to proposed by Thielen et al. (2020) for the SPDI. The index is bounded by SPDI ≤-2.0 and SPDI ≥ 2.O. The positive values indicate humid conditions and the negative values indicates dry conditions (Table 1).

Table 1. Categories to qualify a month according to the values obtained of standardized pluviometric drought index (SPDI) (Thielen *et al*., 2020).

SPDI values	**Category of the month**
≥ 2	Extremely humid
1.5 to 1.99	Very humid
1.0 to 1.49	Moderately humid
-0.99 to 0.99	Near normal
-1.0 to -1.49	Moderate drought
-1.5 to -1.99	Severe drought
≤ -2	Extreme drought

We also calculated the following parameters: the amount of rain in a typical rainy month (r), the rainfall concentration or the number of rainy months (P) and the equitability, which is a relative measurement of rainfall concentration (E). We calculated these parameters using the

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equations proposed by Ezcurra and Rodrigues (1986) for the total period (1941 to 2013) and the two defined periods, where "x" is the amount of precipitation in one month per year and "n" is the number of months (12):

$$P = \frac{(\sum X)^2}{\sum x^2} \quad (3)$$

$$r = \frac{\sum x^2}{\sum x} \quad (4)$$

$$E = \frac{P}{n} \quad (5)$$

Climate type classification

For classification of climate type, analysis of data records for a period of at least 30 years is required (WMO, 2018). To detect changes in the climate type within the last 36 years, the 70-year CCB database was divided into two periods: a) from 1941 to 1976 and b) from 1977 to 2013. For each period, climate type was characterized using the Köppen classification method modified for Mexico by García (1981).

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Results

Trends analysis: Temperature, thermal oscillation and precipitation

T_{min} (Table 2 and Figure 2) and T_{mean} (Table 3 and Figure 3) presented a significant increase of approximately 2 °C from 1941 to 2013 in January to March, and in May. T_{min} also increased 2 °C in the summer months (from June to August) and approximately 1 °C in winter months (November to December; Table 2). Additionally, the T_{mean} increased of approximately 1 °C in June and 2 °C in November. We found no significant trend in the T_{max} from 1941 to 2013 with either of the software packages used (Figure 4). For thermal oscillation, we observed a negative trend by a decrease of *ca.* 2 °C in March, July, August and September (Table 4).

Table 2. Trend analysis of monthly minimum temperatures from 1941 to 2013 in the CCB. The correlation coefficient is shown. Asterisk denotes statistical significance (P < 0.05 and Z < 1.96).

Month	Linear Regression		Mann-Kendall		Trend
	R	***P***	***R***	***Z***	
January	0.03	0.0001*	0.43	3.83*	↑ 2 °C
February	0.02	0.0089*	0.3	3.04*	↑ 2 °C
March	0.03	0.0005*	0.4	3.43*	↑ 2 °C
April	0.01	0.09	0.24	1.79	
May	0.03	0.0001*	0.46	4.00*	↑ 2 °C
June	0.02	0.0000*	0.46	3.86*	↑ 2 °C
July	0.02	0.0046*	0.32	2.59*	↑ 2 °C
August	0.02	0.0002*	0.48	4.09*	↑ 2°C
September	0.02	0.0303*	0.3	2.00*	↑ 2 °C
October	0.02	0.0949	0.23	1.9	
November	0.03	0.0029*	0.38	3.06*	↑ 1 °C
December	0.02	0.0558	0.22	1.96*	↑ 1 °C

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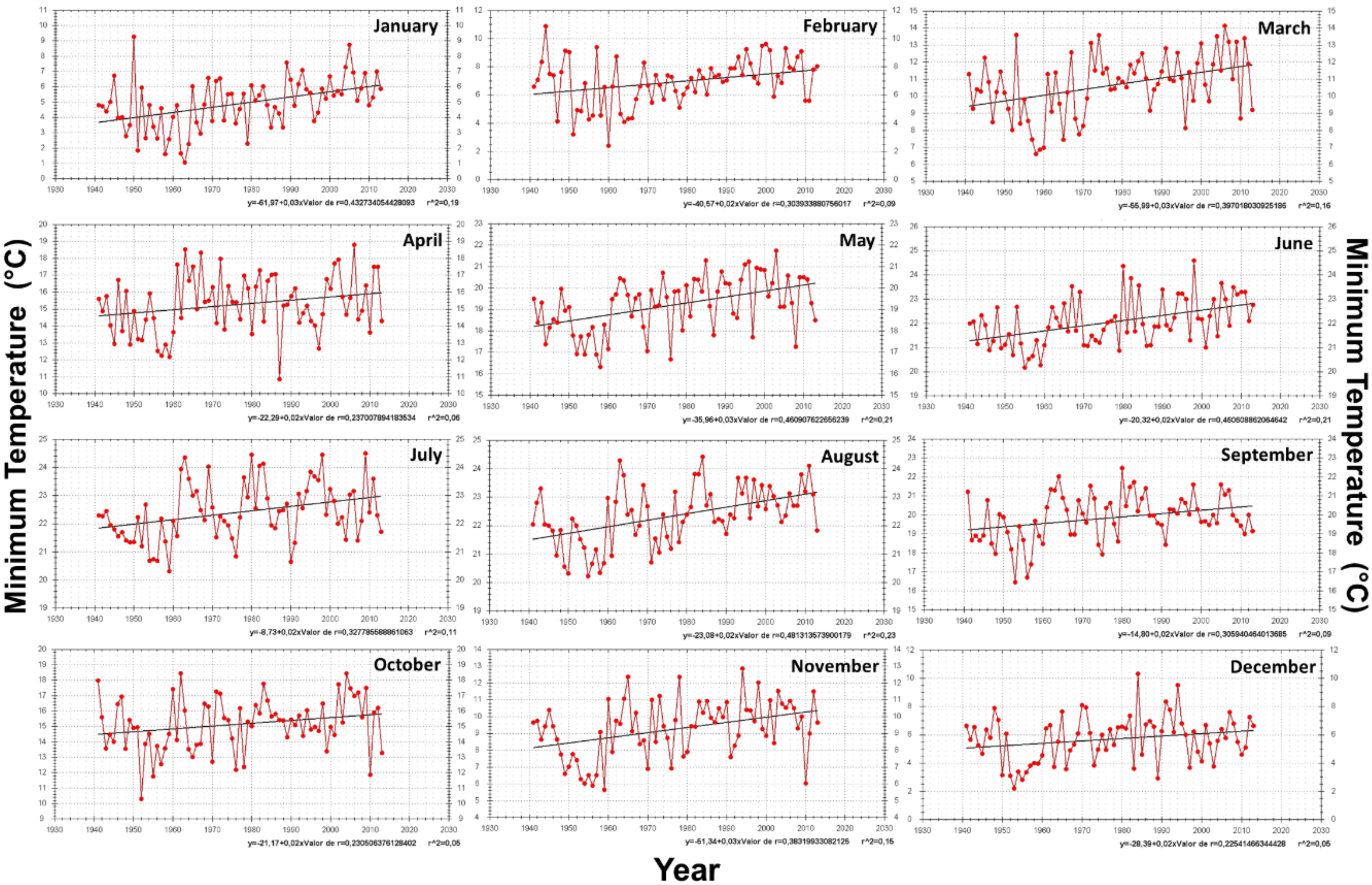

Figure 2. Trend analysis of monthly minimum temperatures from 1941 to 2013 in the CCB. The correlation coefficient is shown.

Table 3. Trend analysis of monthly means temperatures from 1941 to 2013 in the CCB. The correlation coefficient is shown. Asterisk denotes statistical significance (P < 0.05 and Z <1.96).

Month	Linear Regression	Mann-Kendall	Trend

	R	***P***	***R***	***Z***	
January	0.028	0.0088*	0.43	2.36*	↑ 2 °C
February	0.011	0.081	0.3	2.01*	↑ 2 °C
March	0.026	0.007*	0.39	2.43*	↑ 2 °C
April	0.003	0.826	0.23	1.69	
May	0.024	0.0008*	0.46	3.21*	↑ 2 °C
June	0.015	0.0185*	0.46	1.8	↑ 1 °C
July	-0.0003	0.964	0.32	-0.08	
August	0.005	0.4731	0.48	0.69	
September	0.008	0.3042	0.3	0.41	
October	0.015	0.1119	0.23	0.87	
November	0.023	0.0115*	0.38	2.35*	↑ 2 °C
December	0.014	0.1381	0.22	1.12	

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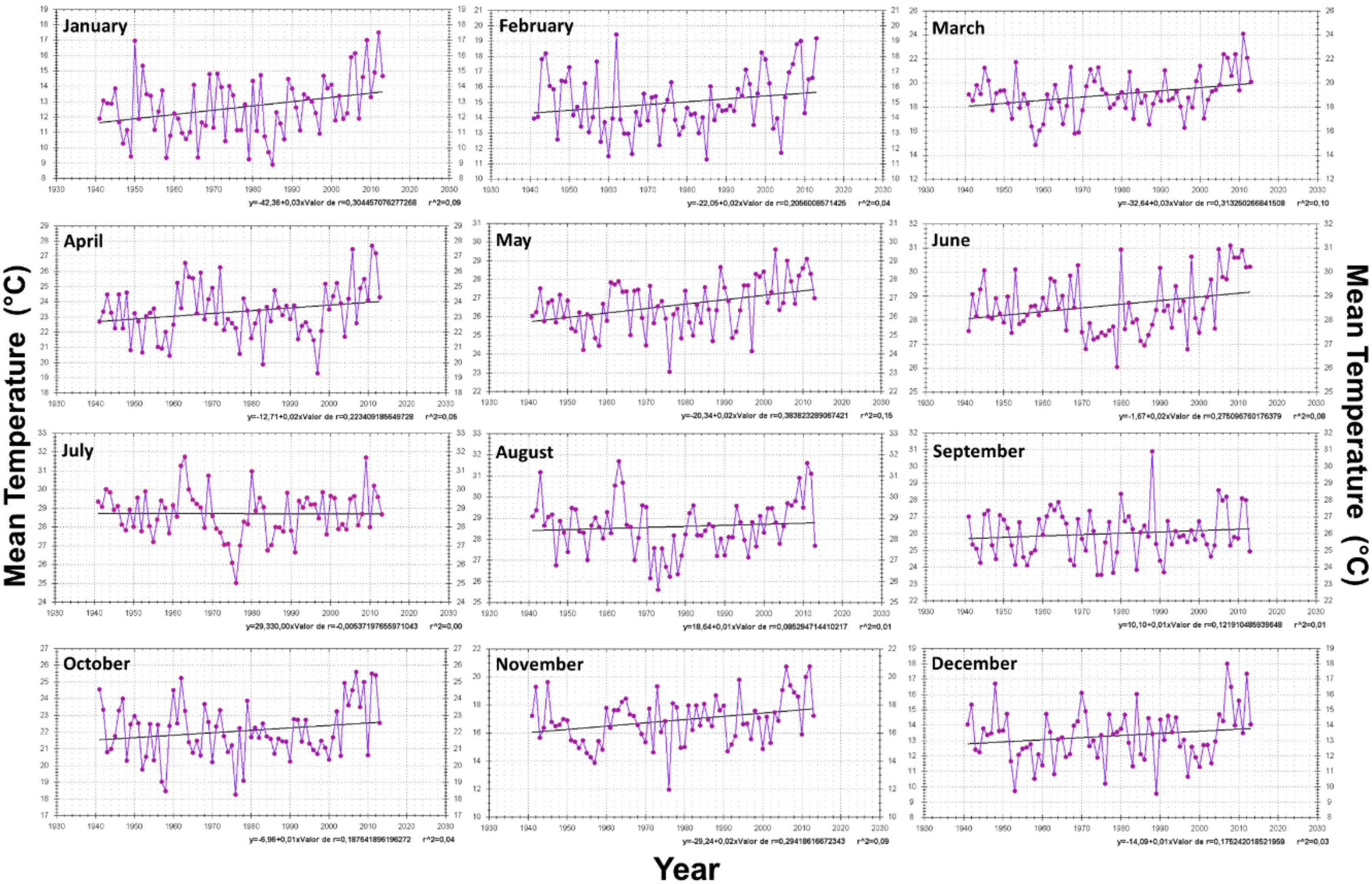

Figure 3. Trend analysis of monthly mean temperatures from 1941 to 2013 in the CCB. The correlation coefficient is shown.

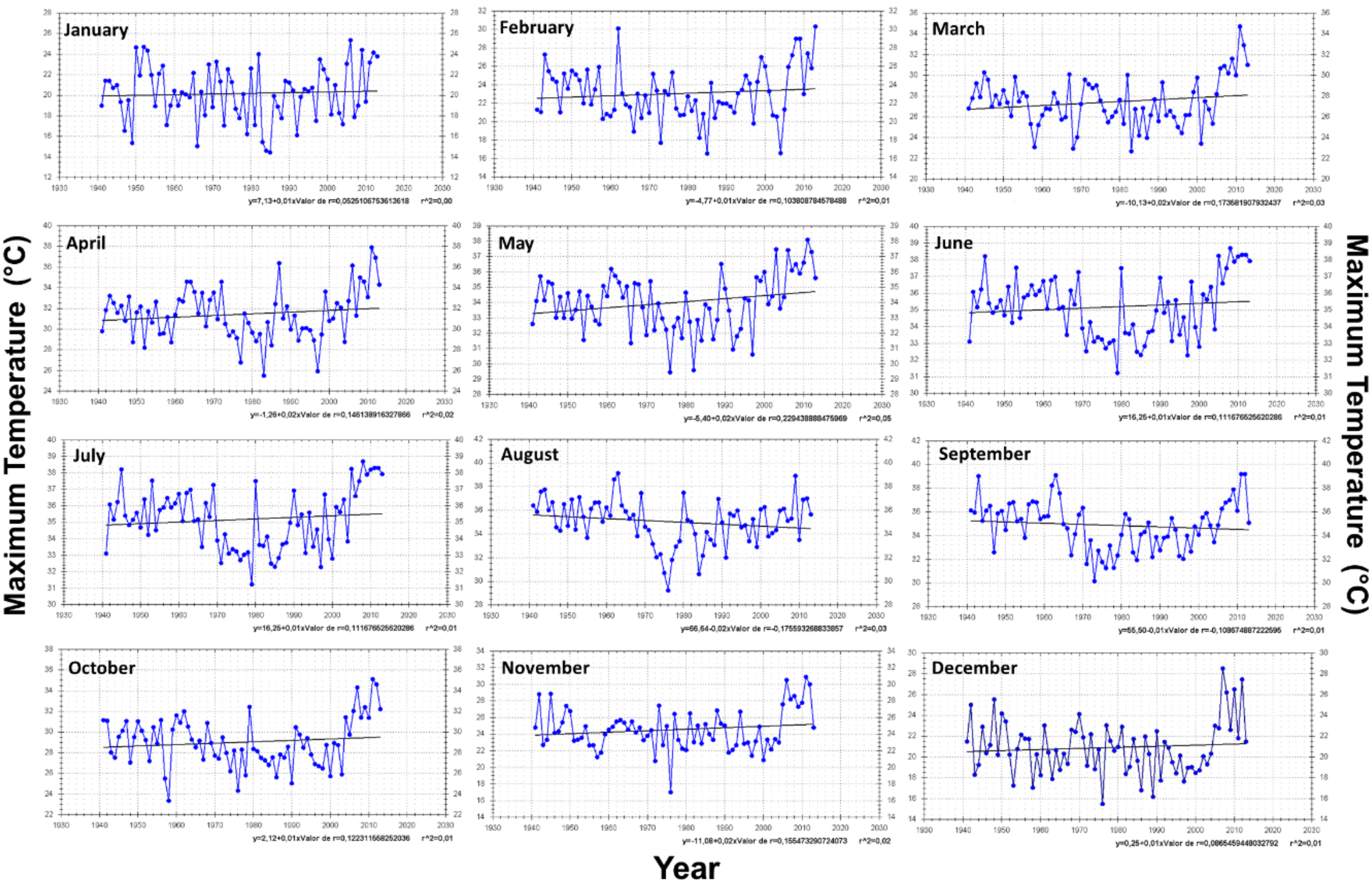

Figure 4. Trend analysis of monthly maximum temperatures from 1941 to 2013 in the CCB. The correlation coefficient is shown.

Table 4. Trend analysis of monthly thermal oscillation from 1941 to 2013 in the CCB. The correlation coefficient is shown. Asterisk denotes statistical significance ($P < 0.05$ and $Z < 1.96$).

Month	Linear Regression	Mann-Kendall	Trend

	R	***P***	***R***	***Z***	
January	-0.01	0.53	-0.113	-1.74	
February	-0.03	0.09	0.007	-0.89	
March	-0.02	0.22	-0.01	-1.98*	↓ 2 °C
April	-0.02	0.11	0.06	-1.14	
May	-0.01	0.34	0.028	-0.95	
June	-0.02	0.06	-0.094	-1.32	
July	-0.04	0.0003 *	-0.281	-2.79*	↓ 2 °C
August	-0.04	0.0003 *	-0.305	-2.66*	↓ 2 °C
September	-0.03	0.012 *	-0.174	-2.23*	↓ 2 °C
October	-0.01	0.46	0.018	-1.06	
November	-0.01	0.50	-0.017	-1.7	
December	0.00	0.88	0.032	-0.61	

For precipitation, we observed an increasing trend in July only. However, it is likely that the lack of observable trends in the other months was due to the wide variability of the data (Table 5).

Table 5. Trend analysis of monthly precipitation from 1941 to 2013 in the CCB. The correlation coefficient is shown. Asterisk denotes statistical significance ($P < 0.05$ and $Z < 1.96$).

Month	**Linear Regression**		**Mann-Kendall**		**Trend**

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	R	**P**	**R**	**Z**	
January	0.00	0.96	0.00	0.07	
February	-0.02	0.78	-0.03	-0.32	
March	0.02	0.70	0.04	0.93	
April	-0.04	0.58	-0.06	-0.71	
May	0.15	0.32	0.11	0.68	
June	0.13	0.42	0.09	0.73	
July	0.37	0.04 *	0.20	2.25 *	↑
August	0.12	0.51	0.07	1.01	
September	0.03	0.89	0.01	-0.06	
October	-0.03	0.81	-0.02	0.01	
November	-0.02	0.85	-0.02	0.3	
December	0.05	0.57	0.06	-0.14	

Analyses of Extreme Climate Events (ECE)

The Chi-square analysis was significant ($p < 0.005$) in all the cases of temperature but was not significant for monthly precipitation (Table 6). For the T_{min} of January, February and May, we observed an increase in the frequency of lower temperature (months increasingly colder) from the

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first (1941-1976) to the second time period (1977-2013; Figure 5a and Figure 6). Likewise, in April, June, July, November and December, we observed a decrease in the lower extremes of T_{min} (months increasingly less cold) from the first to the second period (Figure 5a and Figure 6).

Table 6. Chi-square of frequency of Extreme Climate Events (ECE), in terms of temperature, for two periods in the CCB: 1)1941-1976 and 2)1977-2013, Chi2 value 11.34.

	Chi² Value	**df.**	**P**
T min lower extreme	102.56	12	<0.005
T min upper extreme	134.81	12	<0.005
T max lower extreme	158.83	12	<0.005
T max upper extreme	212.61	12	<0.005
Precipitation upper extreme	2.97	12	NS

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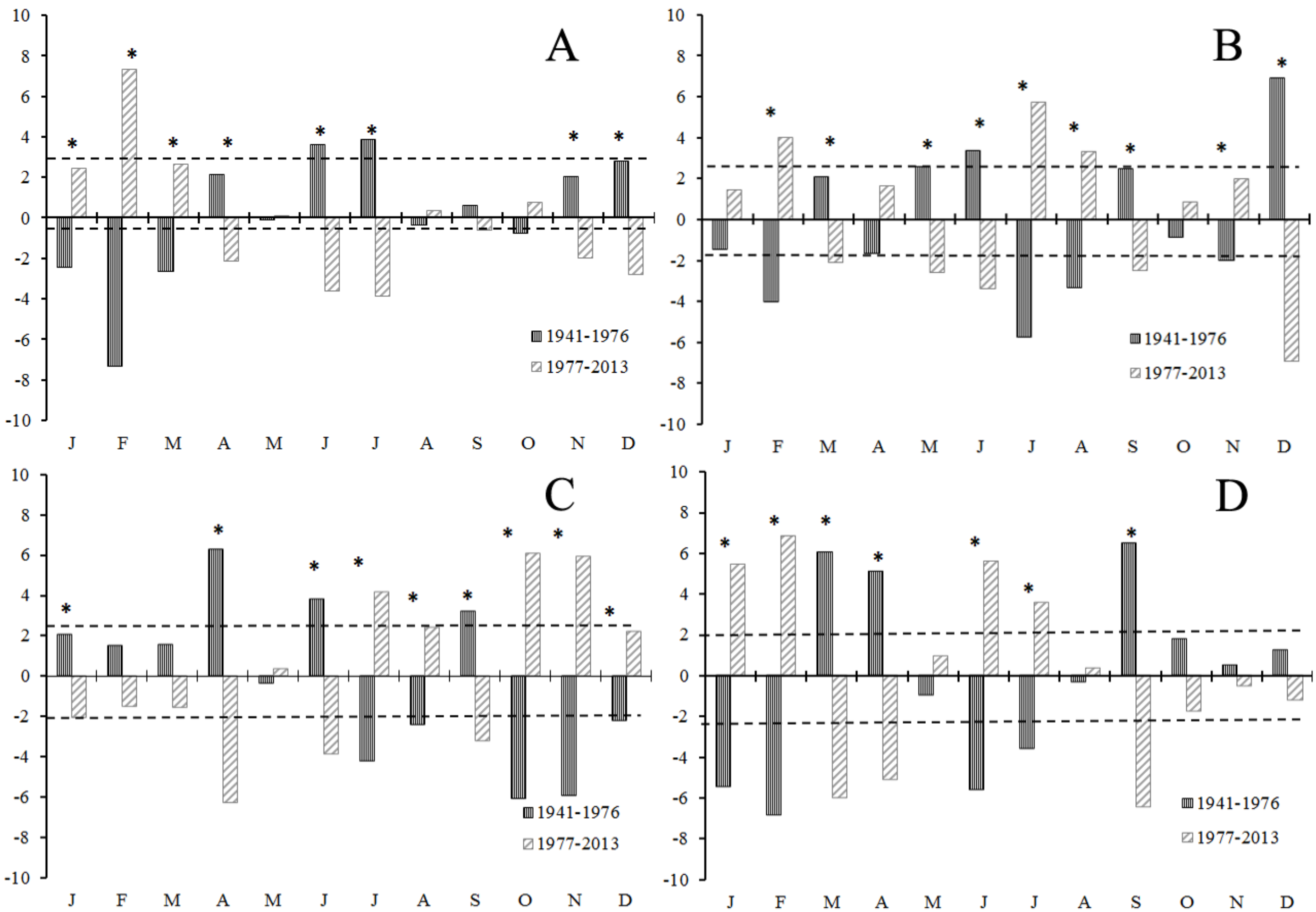

Figure 5. Analysis of residuals from January to December of the frequencies of Extreme Climate Events (ECE) over two periods: 1) 1941-1976 and 2) 1977-2013 in the CCB; A) T_{min} lower extremes, B) T_{min} upper extremes, C) T_{max} lower extremes, and D) T_{max} upper extremes. The asterisk (*) indicates the values above dashed lines that are significantly different to the expected value ($p < 0.05$).

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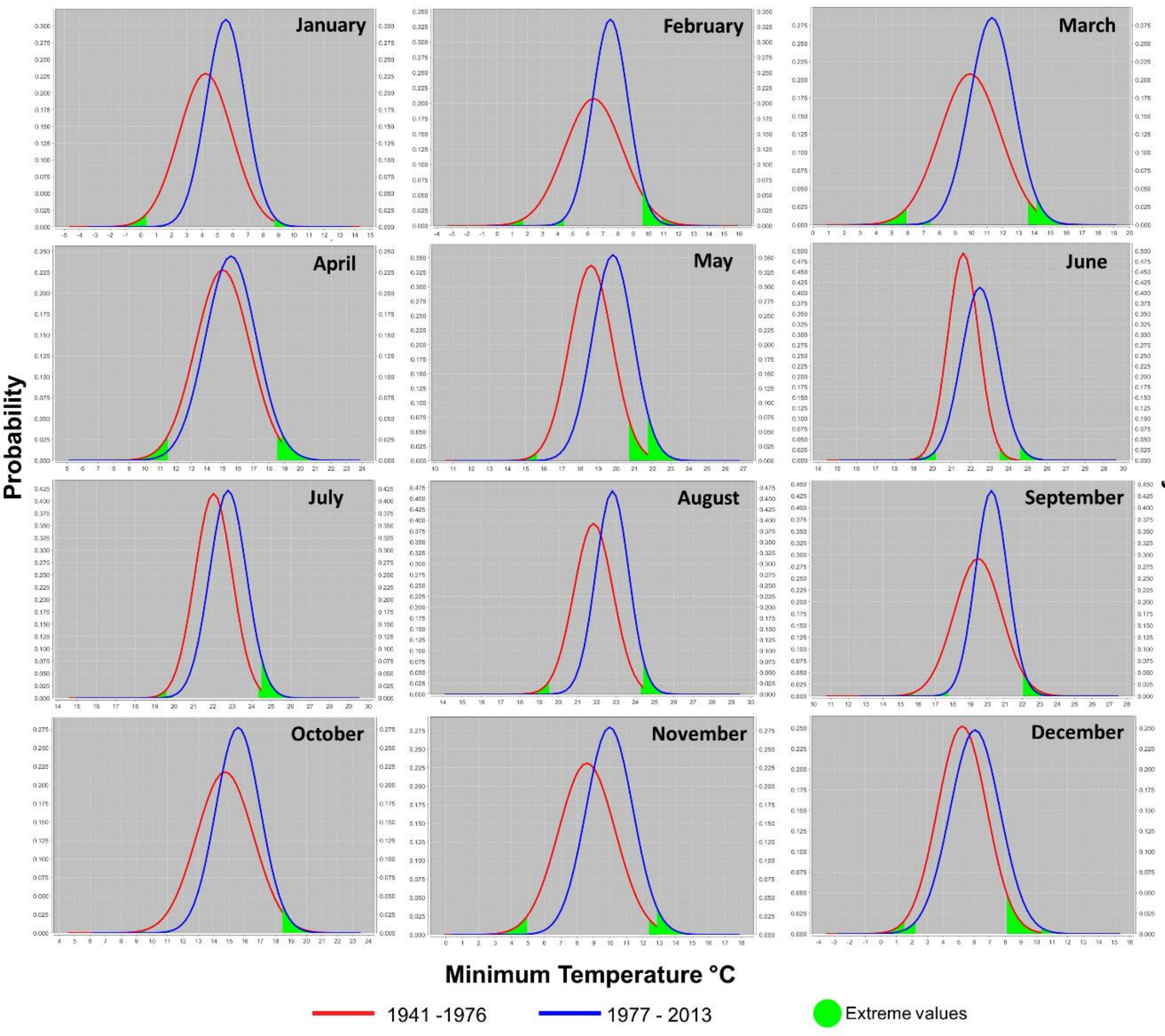

Figure 6. Frequency distribution analysis of minimum temperature from 1941 to 1976 (red line) and from 1977 to 2013 (blue line) in the CCB.

The green color shows the 10th and 90th percentile of distribution in the data series.

For the upper extremes of T_{min} in February, July, August and November, we observed an increase of frequencies (increasingly warmer T_{min}) from the first to the second period (Figure 5b and Figure 6). For the months of March, May, June, September and December, the frequencies of upper extremes (colder T_{min}) of T_{min} decreased from the first to the second period (Figure 5b and Figure 6).

In January, April, June and September, we observed a decrease of the frequencies of the lower extremes (increasingly warmer months) of T_{max} from the first to the second period. In the months of July, August, October, November and December, we observed an increase in the frequencies of lower extremes (fewer warm months) of T_{max} from the first to the second period (Figure 5c and Figure 7).

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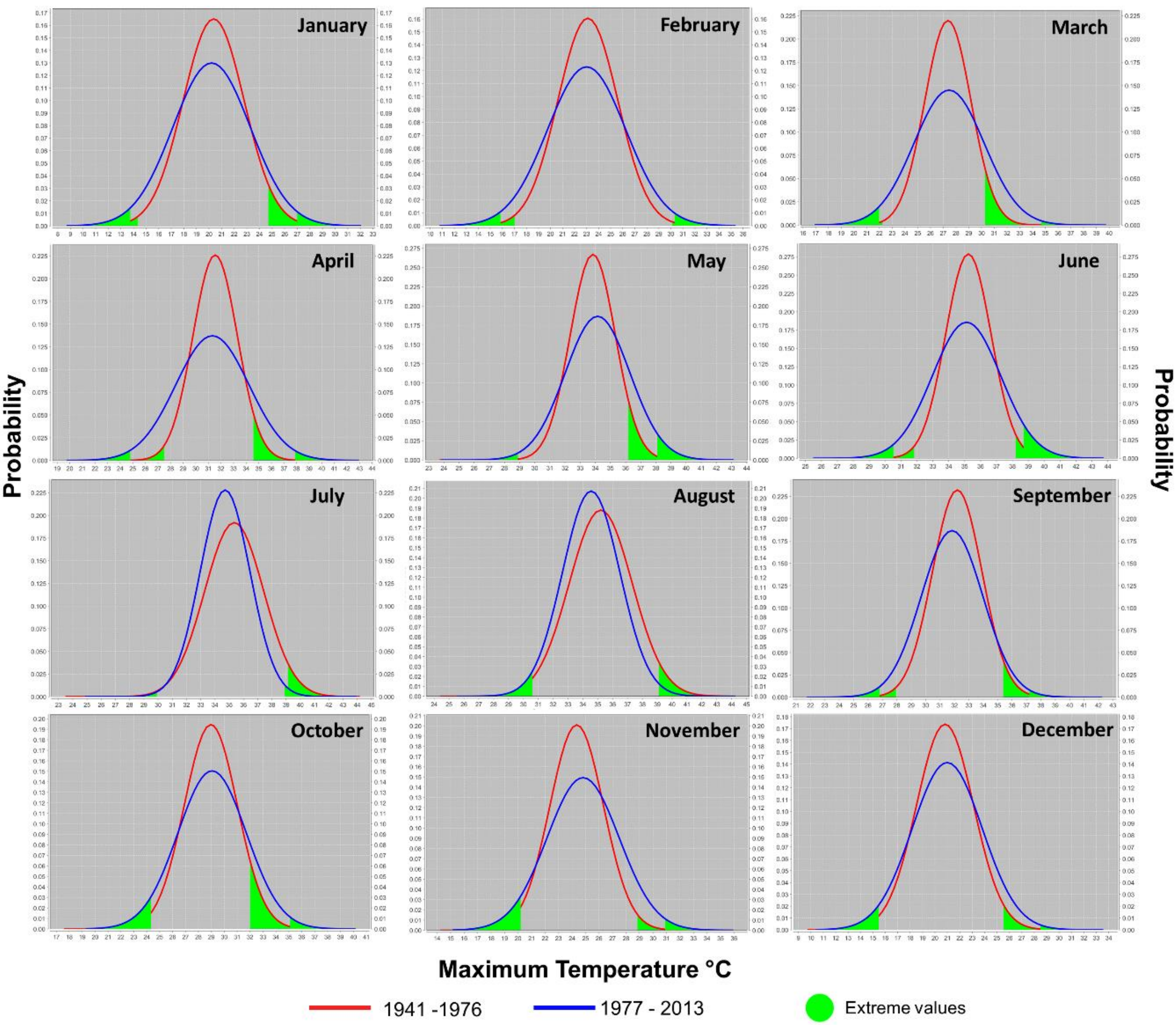

Figure 7. Frequency distribution analysis of maximum temperature from 1941 to 1976 (red line) and from 1977 to 2013 (blue line) in the

CCB. The green color shows the 10th and 90th percentile of distribution in the data series.

In the upper extremes of T_{max}, we observed in January, February, June and July an increase of frequencies (increasingly warmer months) from the first to the second period. In March, April and September, we observed a decrease of frequencies of upper extreme events (fewer warm months) of T_{max} from the first to the second period (Figure 5d and Figure 7).

We did not find significant differences in the frequencies of extreme monthly precipitation between the first and second periods (Table 5).

Analysis of Precipitation

We identified a trend of increasing precipitation in the month of June using the Mann Kendall test (Table 5). Before the year 1985, the SPDI values don't show years classified with severe drought or whit extreme drought (Figure 8). After the year 1985, two years (2013 and 2012) were classified with severe drought and three years with extreme drought (1988, 1989 and 1990). Finally, 13 years classified as extremely humid (1949, 1958, 1971, 1976, 1977, 1978, 1979, 1986, 1992, 1997, 2003, 2008, 2010).

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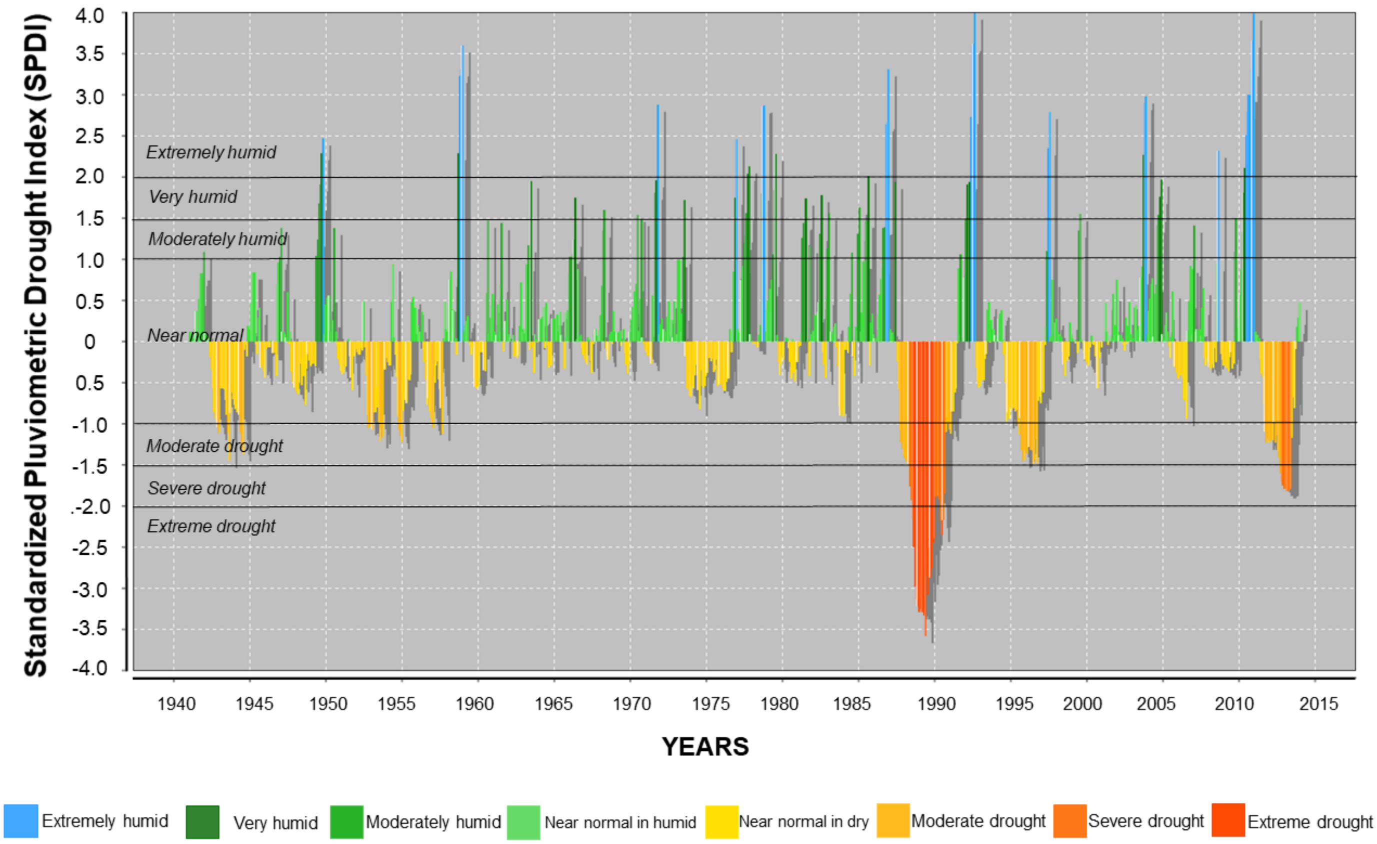

Figure 8. Standardized pluviometric drought index (SPDI), calculated from 1941 to 2013 in the CCB.

The calculated "r", "P" and "E" values, respectively, for the complete period (1941-2013) were 54 mm, 277 and 0.32 mm; for the first period, these values (1941-1976) were 51, 137 and 0.32 mm and for the second period (1977-2013), they were 57, 142 and 0.32 mm.

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Climate type classification for two periods

For the two defined time periods, we found a change of climate type. For the first period from 1941 to 1976, the climate classification according to Köppen was BWhw(x´)(e´). This climate is defined as very dry, semi-warm, and had an annual average temperature of 21.4 °C; the temperature of the coldest month (January) was 12.3 °C, while that of the hottest month (July) was 28.4 °C. Rains were markedly seasonal (summer), the percentage of rains that fell in winter was 10.7 %. Thermal oscillation was extreme (Figure 9a).

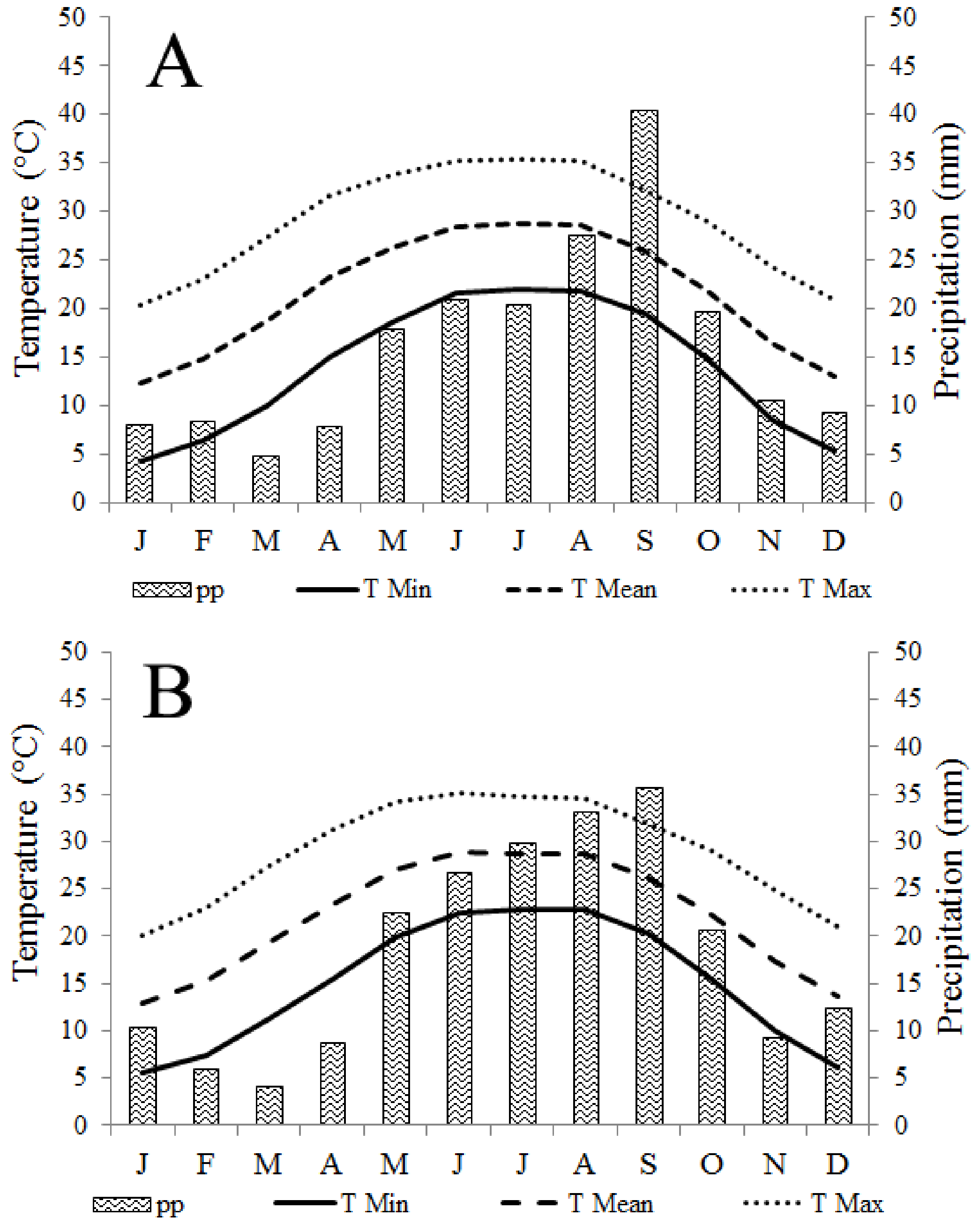

Figure 9. Monthly minimum, average and maximum values for temperature and precipitation recorded over two periods: a) From 1941 to 1976 and b) From 1977 to 2013.

In the second period, from 1977 to 2013, the climate classification was BWhwx´(w)(e´). This climate is defined as very dry, semi-warm, and presented an annual average temperature of 21.9 °C. The temperature of the coldest month (January) was 12.9 °C, while that of the hottest month (July) was 28.8 °C. Summer rains concentrated around 90 % of the annual precipitation and the percentage of winter rain was 9.3 %. Thermal oscillation was very extreme (Figure 9b).

The change in the climate type classification from first to the second period was therefore mainly caused by a decrease in the temperature of the coldest month (January), an increase in the temperature of the warmest month (July), higher annual thermal oscillation and a reduction in the percentage of winter rain.

Discussion

Temperature

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Our working hypotheses were increases in atmospheric temperature and the frequency of temperature ECEs, as proposed for the Chihuahuan desert by Loarie *et al*. (2009) and by the IPCC scenarios (IPCC, 2012). For our study site, T_{min} increased in almost all the months but T_{mean} increased only in the summer months. Moreover, the frequency of lower T_{min} increased in the winter months, while the frequency of upper event extremes increased during the summer months, as well as the extreme events of T_{max}. This means that the winters were colder, and the summer months were warmer with higher T_{min} and T_{max} extreme events, increasing the frequency of heat waves over the last 36 years. The heat wave is defined by the increment of frequencies in the upper extremes (90^{th} percentile of distribution) of T_{max} of June and July (the warmer months in the CCB) as proposed by several authors (Meehl & Tebaldi, 2004; Peng *et al*., 2011). Additionally, the increment of frequencies in the upper extremes (90th percentile of distribution) of T_{min} on July and August in the second period, suggests an increase in warm nights, suggesting an heat wave as reported by previous authors (Meehl & Tebaldi, 2004; Peng *et al*., 2011).

Positive trends of T_{mean} in the summer months have also been found in other desert ecosystems, such as the Sahara desert in Libya (Mamtimin, Et-Tantawi, Schaefer, Meixner, & Domroes, 2011) and Almeria in Spain (Del-Río, Herrero, Pinto-Gomes, & Penas, 2011); while other studies have reported T_{mean} increments throughout the year in other desert sites such as Jerusalem, Tripoli (Hasanean, 2001) and Iran (Tabari & Hosseinzadeh-Talaee, 2011; Tabari, Somee, & Zadeh, 2011).

As expected, we detected a positive trend in T_{min}, implying that T_{min} has become warmer in recent years for most months of the year. This was found in other desert ecosystems in Iran (Ben-Gai *et al*., 1999; Tabari *et al*., 2011), Jordan (Hamdi, Abu-Allaban, Elshaieb, Jaber, & Momani, 2009) and North Carolina in the USA (Boyles & Raman, 2003) and was also observed in other regions of the world, such as Italy (Brunetti, Buffoni, Maugeri, & Nanni, 2000), Turkey (Türkes, Sümer, & Kiliç, 1996). It was also observed at global level by Easterling *et al*. (1997), and Vose, Easterling and Gleason (2005). Several studies in other ecosystems (Boyles & Raman, 2003; Brunetti *et al*., 2000; Easterling *et al*., 1997; Boyles & Raman, 2003; Brunetti *et al*., 2000; Easterling *et al*., 1997; Vose *et al*., 2005) have attributed the summer increase of the T_{min} in specific years to abnormalities in the ENSO combined with an increase of the positive phase of NAO and is probable that in our study site the increase in T_{min} may be related with this phenomena. However, there was an increased frequency of lower extreme events for T_{min} during the winter months, a finding also reported for Israel (Ben-Gai *et al*., 1999), Utah in the USA (Santos, 2011) and Tlaxcala in Mexico (López-Díaz *et al*., 2013). This result indicates that winters with colder nocturnal events in the CCB have been more frequent during the last 36 years. The increase in T_{min} of winter months was explained by the negative phase of NAO during the winter months in other ecosystems (Boyles & Raman, 2003; Brunetti *et al*., 2000; Easterling *et al*., 1997; Vose *et al*., 2005) we propose that this phenomenon could also cause colder winters in specific years in our study site.

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In contrast, the frequency of the upper extremes for T_{min} and T_{max} during the summer increased over the last 36 years, promoting higher summer nocturnal and diurnal temperatures. Other studies in North America (Hasanean, 2001; López-Díaz *et al*., 2013; Peterson *et al*., 2013) observed that in the summer months the increase in extreme temperature was produced by El Niño events in combination with the positive phase of the Pacific Decadal Oscillation (PDO), and we proposed that these phenomena could also generate the changes in the upper extremes for T_{min} and T_{max} during the summer in our study site. These results have also been reported in other studies, Alexander *et al*. (2006) observed a marked increase of warm nocturnal temperatures at global level throughout the year, while several authors have found a higher frequency of upper extreme temperature events of T_{max} during the summer months (Ben-Gai *et al*., 1999; López-Díaz *et al*., 2013; Santos, 2011).

Precipitation

In the case of precipitation, our working hypothesis had been an increase in precipitation variability, but we found that the precipitation did not show any temporal trend, due to the large variability of monthly precipitation. This variability obscured any trend in the frequency of extreme precipitationevents. In desert ecosystems, precipitation events are scarce and very erratic, producing a skewed temporal distribution of the data (Ezcurra & Rodrigues, 1986), as was the case in our study site. It is possible that this behavior differed from the expected trend in the CCG and ECE scenarios for the Chihuahuan Desert, explained mainly by the effect of geographical barriers on climatic dynamics within CCB. This lack of a trend in precipitation throughout the year was also observed in other desert ecosystems in Israel (Modarres & Silva, 2007), Jordan (Hamdi *et al*., 2009) and India (Jain, Kumar, & Saharia, 2013).

Jain and Kumar (2012) expected that the inter-annual variability of annual precipitation could be increased by GCC during the 21stcentury, mainly as a result of the increasing frequency and intensity of ECE (D'Odorico & Bhattachan, 2012; IPCC, 2012). However, while we did not observe a significant change in the precipitation frequency of precipitation ECE, the records of annual precipitation for the second period show a higher incidence of years with annual precipitation higher than 300 mm distributed throughout the year (nine years: 1978, 1981, 1984, 1986, 1991, 1992, 1997, 2003 and 2010), in contrast to the first period where the precipitation was concentrated in the tropical cyclone seasons (5 years: 1949, 1958, 1963, 1971 and 1976).The calculated precipitation value for a typical rainy month for CCB (1941-2013) was 54 mm, and it increases from 51 mm to 57 mm from the first to the second analyzed period. We also observed a higher incidence of years with precipitation below 100 mm in the second period (6 years: 1983, 1988, 1994, 1995, 2011 and 2012) compared to the first period (4 years: 1942, 1952, 1956 and 1959). These results are according to the SPDI values, we observed an apparently increased in frequency and intensity of extreme drought

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and extreme precipitation events after the year 1985. The increased frequency of heavy precipitation events has been attributed to years with strong cyclones from the Gulf of Mexico, produced by a combination of La Niña and either the NAO or the PDO (Boyles & Raman, 2003; Brunetti *et al*., 2000; Vose *et al*., 2013), while drought events have been associated in other ecosystems with warm subtropical anticyclones attributed to the coincidence of El Niño with either the NAO or the PDO (Boyles & Raman, 2003; Brunetti *et al*., 2000; Peterson *et al*., 2013). Unfortunately, the incidences of intensive ENSO or NAO abnormalities have increased in recent decades (IPCC, 2013), promoting precipitation variability.

In arid and semi-arid regions such as the CCB, changes in temperature and precipitation will affect environmental water balances, increasing the water stress experienced by organisms and leading to a significant reduction in ecosystem productivity. Unfortunately, our results suggest that winters will become colder and summers will become warmer with a high variability in the availability of water in CCB, increasing the environmental stress for organisms. For this reason, is very important to fully understand how climate is changing in order to design appropriate management strategies for adapting to such climate variability in the near future. Moreover, local climate studies, such as the present study, are critical for the calibration and development of global scenarios under GCC (Tabari & Hosseinzadeh-Talaee, 2011).

Conclusions

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We observed a higher climate variability in the recent years in the desert of Cuatro Ciénegas Basin Mexico. At CCB, T_{min} increased in almost all the months of the study period, but T_{mean} increased only in the summer months. The frequency of lower T_{min} increased for the winter months, while the frequency of upper event extremes increased during the summer months, as did the extreme events of T_{max}. This implies that the winters have become colder and the summer months warmer, increasing the frequency of heat waves over the last 36 years. Monthly precipitation showed high variability, which obscured any potential trend in the frequency of extreme precipitation events; nevertheless, over the last 36 years, frequencies of events of both intensive precipitations associated with tropical cyclones and intense drought probably associated with ENSO were higher than before. As a consequence, the organisms are expected to face higher levels of environmental stress.

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