



Analysis of the trends in precipitation and precipitation concentration in some climatological stations of Mexico from 1960 to 2010

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Abstract

Analysis of precipitation trends as well as the observed trends in precipitation concentration can be useful tools for the identification of natural hazards. This study aimed to analyze the trends in precipitation and precipitation concentration at the seasonal and annual levels in Mexico from 1960 to 2010. To do this, an entropy-based concentration index was used to calculate the concentration of precipitation at 44 climatological stations distributed throughout the country. The trend analysis was developed based on the Mann–Kendall test. There were fifteen significant precipitation trends at the annual level, and the numbers of positive and negative trends were nearly even. The interannual average of the concentration index ranged from 0.084 to 0.265, although extreme values of up to 0.56 were observed at the annual level and of up to 1 at the seasonal level. There were more positive trends than negative trends in the concentration index. The comparison of the trends of the precipitation and the concentration index showed an increase in precipitation at some stations with an associated decrease in the concentration index. On the other hand, decreases in precipitation at other stations were accompanied by increases in the concentration index. The first case did not seem to represent risk because the conditions suggested a more regular precipitation pattern. However, the second case could be considered a cautionary indicator, especially in the northern region, where it could signal the potential for drought.

Keywords Precipitation · Concentration index · Entropy-based concentration index · Seasonal precipitation · Precipitation trend

1 Introduction

In recent years, concerns about the possible effects of climate change have led to the several investigations focused on the analysis of the behavior and trends of climatological variables. Among these variables, one of the most investigated has been precipitation due to the updated results of the IPCC Fourth Assessment Report, which reported

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an increase in heavy precipitation during the last century. It was found that in most cases, precipitation has become much heavier than average (Trenberth et al. 2007). This conclusion has been supported by De Luis et al. (2011) and Caloiero (2014).

The interest in the analysis of the precipitation behavior is due to the potential consequences of a change in precipitation behavior. As highlighted by Ferrari et al. (2013), changes in precipitation may be problematic for economic activities related to agriculture, energy production and drinking water supply and can cause natural hazards, such as droughts, floods and erosion (Caloiero 2014; Liu and Xu 2016; Zamani et al. 2018). In this sense, researchers, such as De Risi et al. (2020) and Byakatonda et al. (2020), have pointed out that in recent decades, the incidence of weather-related disasters has increased. Thus, analysis of the spatial and temporal variability of precipitation is very important for planning actions to avoid damage related to this kind of natural hazard (Todeschini 2012; Zamani et al. 2018).

Studies of precipitation have mainly focused on frequency and intensity; in recent years, the concentration of precipitation at the monthly level has been evaluated with the precipitation concentration index proposed by Oliver (1980) and at the daily level with indices such as the concentration index of Martín-Vide (2004).

In the last decade, precipitation concentrations have been evaluated worldwide, as shown by the research works of De Luis et al. (2011), Li et al. (2011), Benhamrouche and Martín-Vide (2012), Cortesi et al. (2012), Coscarelli and Caloiero (2012), Suhaila and Jemain (2012), Shi et al. (2013, 2014), Huang et al. (2013), Caloiero (2014), Benhamrouche et al. (2015), Patel and Shete (2015), Monjo and Martín-Vide (2016), Yesilirmak and Atatanir (2016), Mayer et al. (2017), Serrano-Notivoli et al. (2017), Zubieta et al. (2017), Llano (2018), Vyshkvarikova et al. (2018), Zamani et al. (2018), Meseguer-Ruiz et al. (2019), Sarricolea et al. (2019), and Vélez et al. (2019). However, in a few of these studies, the interannual seasonal behavior of the precipitation concentration was analyzed. In these studies, the concentration index of Martín-Vide (2004) was used; however, in places where precipitation is very low, especially on a seasonal scale, it is difficult to adjust an exponential curve to calculate the concentration index. Under these circumstances, an alternative for the calculation of the precipitation concentration is the use of entropy-based concentration indices, which have shown good performance, as highlighted by Monjo and Martín-Vide (2016) and Li et al. (2017).

In Mexico, precipitation varies significantly in both space and time (Méndez et al. 2008). According to the water statistics of Mexico from 2018 (CONAGUA 2018), precipitation increased in the north–south direction due to latitudinal influence (Méndez et al. 2008). Rainfall in the northwest and northeast hardly reached an annual average of 250 mm, while the southeast and some regions along the southern Pacific coast had an annual average between 2000 and 4000 mm (CONAGUA 2018).

There have been few studies dedicated to the analysis of precipitation at the national level in recent decades, and the conducted studies have been focused mainly on the analysis of the spatial distribution of this climatic variable. For example, García (2003) presented an analysis of the precipitation distribution in the Mexican Republic based on the behavior of the total annual rainfall, the winter rain percentage, and the rainfall distribution throughout the year. On the other hand, Giddings et al. (2005) analyzed a series of the standardized precipitation index (SPI) to divide the country into zones according to the behavior of this index. In a more recent study, Méndez et al. (2008) analyzed the temporal trend of seasonal rainfall in Mexico from 1920 to 2004 and classified the country into zones according to the seasonal rainfall regime.

The previously mentioned study concluded that in recent years, evidence has been found that the climate in Mexico had exhibited different fluctuations from those recorded in the past. In particular, they found that on average, the trends of the highest precipitation increase were observed during summer. Additionally, there were important increases in precipitation in the spring and in semiarid regions of the country and important increases in precipitation in spring and winter, which are the seasons in which lower quantities of precipitation are recorded annually. On the other hand, geographically, the behavior of the trends showed that the arid and semiarid regions located in northern Mexico had experienced an increase in the precipitation of approximately 2% of the total annual precipitation, while the central regions of the country and the coasts of Mexico's Gulf (rainy zones) have shown a significant decrease of 1% of the annual rainfall on average. The above results suggested the possibility of some natural hazards, mainly in regions where increases in precipitation and increases in its concentration had been observed.

However, to date, no studies have analyzed the concentration of precipitation at the national level, although there are certain approximations in some regions of the country, such as the studies carried out in the Río Grande basin in Morelia by Roblero-Hidalgo et al. (2018) and in the state of Jalisco by Núñez-González (2020). Thus, the objective of this study consisted of the analysis of the seasonal and annual trends of precipitation in Mexico for the period from 1960 to 2010 and then in the analysis of the behavior and the trend of the interannual seasonal and annual precipitation concentrations to determine the possible future occurrence of wet or dry spells according to the behavior of the trends of precipitation and its concentration.

2 Data and methods

To analyze the concentration of daily precipitation in Mexico, the National Meteorological Service of Mexico (NMS 2019) data series with the longest records for a common period were used. The data series were tested for missing data, and the time series with less than 10% missing data were selected for the study. The time series were checked for homogeneity problems using the methodology proposed by Wang et al. (2010) through the package `RHtests_dlyPrcp` in the statistical software R (R Core Team 2013). After the quality control and homogeneity test, forty-four climatological stations with a common period of observation from 1960 to 2010 were selected. This observation period was similar to the time period considered in the majority of the research studies focused on the precipitation concentration. The locations of the climatological stations selected for the study are shown over the digital elevation model of Mexico in Fig. 1.

For the analysis at the seasonal level, the annual precipitation data were partitioned in the following manner: March, April, and May were classified as spring; June, July, and August as summer; September, October, and November as autumn; and finally, December, January, and February as winter.

The trend analysis of the annual and seasonal precipitation and the trend of the concentration index were developed according to the nonparametric trend test of Mann–Kendall (Kendall 1975; Mann 1945), which has been widely suggested by the World Meteorological Organization (Huang et al. 2013). This test is based on the S statistic, which is defined as follows:

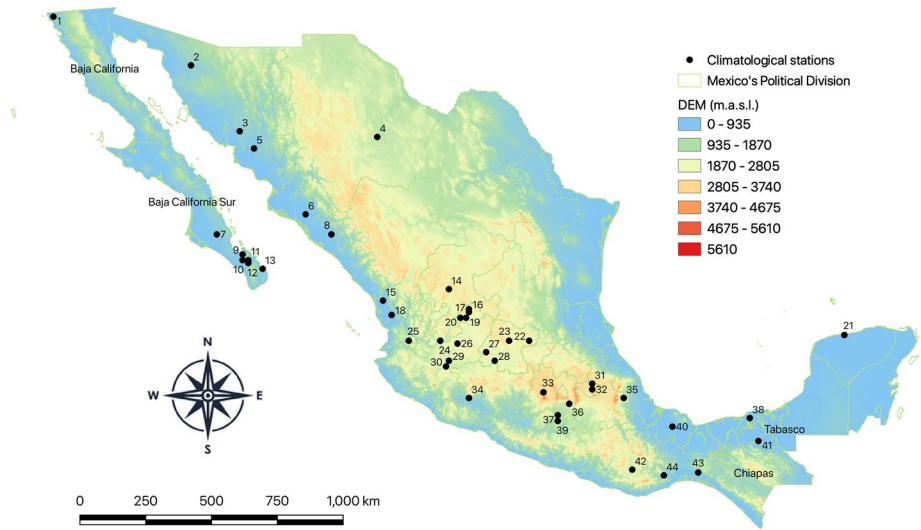


Fig. 1 Locations of the climatological stations considered in the calculation of the concentration index

$$S = \sum_{k=1}^{n-1} \sum_{j=k+1}^n \text{sgn}(x_j - x_k) \tag{1}$$

where n is the data length, x_j is the value of the j th data, and $\text{sgn}(x)$ is the sign function, which is defined as follows:

$$\text{sgn}(x) = \begin{cases} +1 & (x_j - x_k) > 0 \\ 0 & (x_j - x_k) = 0 \\ -1 & (x_j - x_k) < 0 \end{cases} \tag{2}$$

When $n \geq 8$, the S statistic is almost normally distributed, with mean $E(S) = 0$, and the variance is calculated as follows:

$$\text{Var}(S) = \frac{n(n-1)(2n+5) - \sum_{i=1}^m t_i(t_i-1)(2t_i+5)}{18} \tag{3}$$

where m represents the number of tied groups, and t_i is the size of the i th tied group. In this manner, the statistic test can be computed as follows:

$$Z = \begin{cases} \frac{S-1}{\sqrt{\text{Var}(S)}} & S > 0 \\ 0 & S = 0 \\ \frac{S+1}{\sqrt{\text{Var}(S)}} & S < 0 \end{cases} \tag{4}$$

The null hypothesis of no trend was rejected at the 95% significance level if $|Z| > 1.96$.

Next, the magnitude of the slope was estimated using the nonparametric approach proposed by Sen (1968) as follows:

$$\beta = \text{median} \left(\frac{X_j - X_k}{j - k} \right) \quad (5)$$

where β is the estimate of the slope and X_j is the j -th observation with $j > k$.

The calculation of the precipitation concentration index was based on the adaptation made by Monjo and Martin-Vide (2016) of the entropy index proposed by Theil as an inequality indicator based on the Shannon entropy, which is given by the following equation:

$$\text{TI} = \frac{1}{N \ln N} \sum_{i=1}^N \left(\frac{p_i}{\bar{p}} \cdot \ln \frac{p_i}{\bar{p}} \right) \quad (6)$$

where TI is the concentration index, N is the number of rainy days during the year or the season, p_i is a precipitation event, and \bar{p} is the mean precipitation of the studied year or season.

An alternative for the calculation of the precipitation concentration based on the entropy concept was proposed by Li et al. (2017), which was called the Q index. This index differs from the TI index mainly in the sample size (N) needed for its calculation. Instead of using the number of rainy days, the Q index uses a fixed value of N , 365 or 366 for a year, and 90, 91, or 92 for the climatological seasons.

3 Results and discussion

3.1 Behavior of precipitation in Mexico from 1960 to 2010

The distribution of the mean annual precipitation in Mexico during the period from 1960 to 2010 is shown in Fig. 2 according to spline interpolation. The lowest values of precipitation were observed in the northern portion of country in the state of Baja California Sur, while the highest values were located in the southwest in the state of Chiapas. This distribution coincided with that reported by CONAGUA (2018), and it can be mainly attributed to latitudinal influences and atmospheric circulation patterns (Garcia 2003; Mendez et al. 2008). The average annual precipitation observed from 1960 to 2010 was less than the normal precipitation of the 1951–2010 period in two-thirds of the climatological stations. This behavior was observed throughout the entire territory, which suggested that in recent years, precipitation has decreased in Mexico. Seasonally, the precipitation was distributed as follows: of the total annual, 7.1% occurred in spring, 54.8% in summer, 29.3% in autumn, and 8.8% during winter. The precipitation distribution showed a marked pattern of summer and autumn rainfall (Fig. 2c and d); more than 80% of the precipitation occurred in most of the country during these seasons. The exception to this distribution was seen at climatological station number 1, where the highest percentages of precipitation were seen during winter and spring, although compared with other stations, the amount of precipitation registered at this station was very low. This behavior has already been pointed out by Méndez et al. (2008) for some stations in the north of the country. According to García (2003), the precipitation in the winter in these regions may be due to the presence of cold air masses that move southward from Canada and the USA, occasionally producing precipitation.

The trend analysis of the precipitation on an annual scale showed that only 10 data series had significant trends at a >95% confidence level and the other 5 series had significant trends at a 90% confidence level. In a general manner, eight series showed

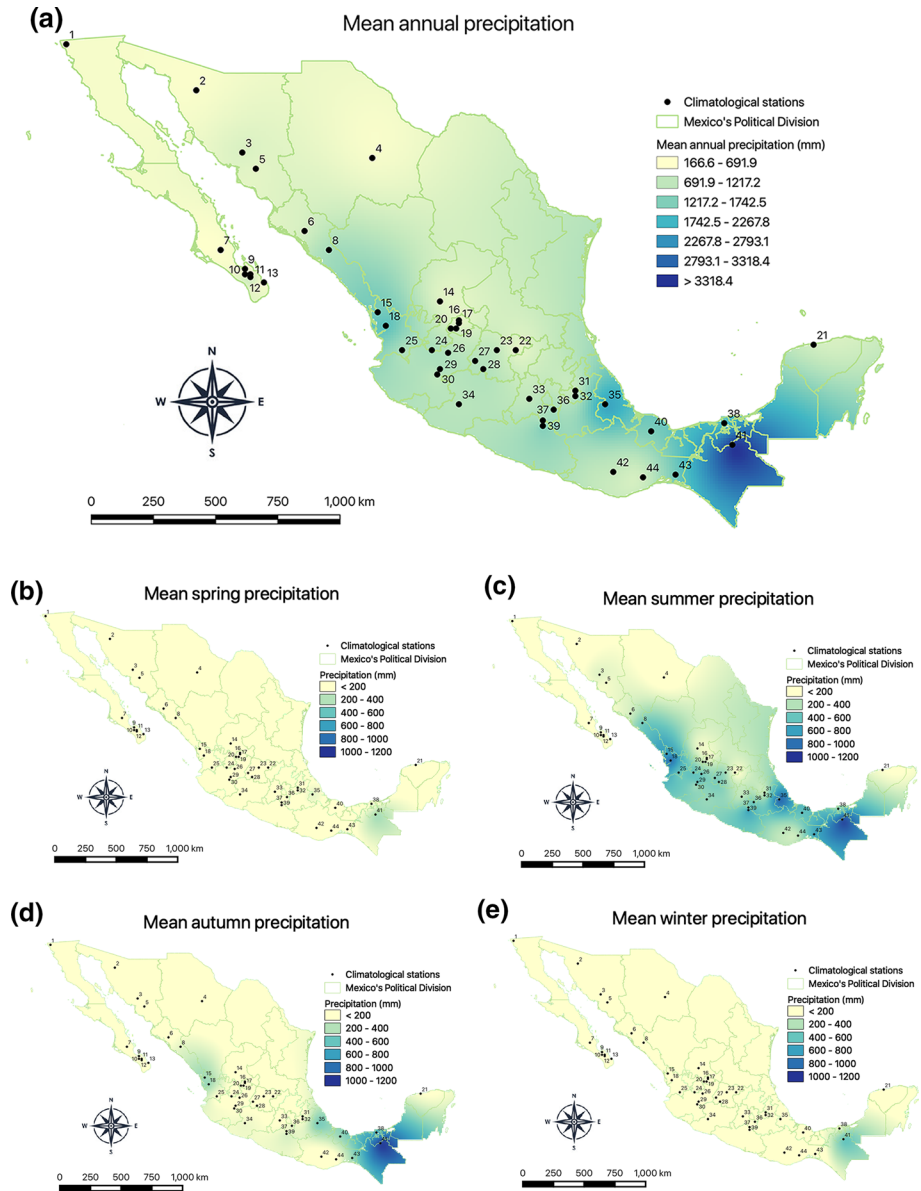


Fig. 2 Annual and seasonal mean precipitation in Mexico from 1960 to 2010

positive significant trends, while another seven showed negative significant trends. The magnitude of the positive significant trends ranged from 1.6 to 9.6 mm per year, and that of the negative significant trends ranged from 2.5 to 7 mm per year. Despite the low number of significant trends, an important decrease in precipitation was seen in some regions in the center and northwest of the country (Fig. 3), which could be relevant because according to the water statistics of Mexico in these regions, these areas have

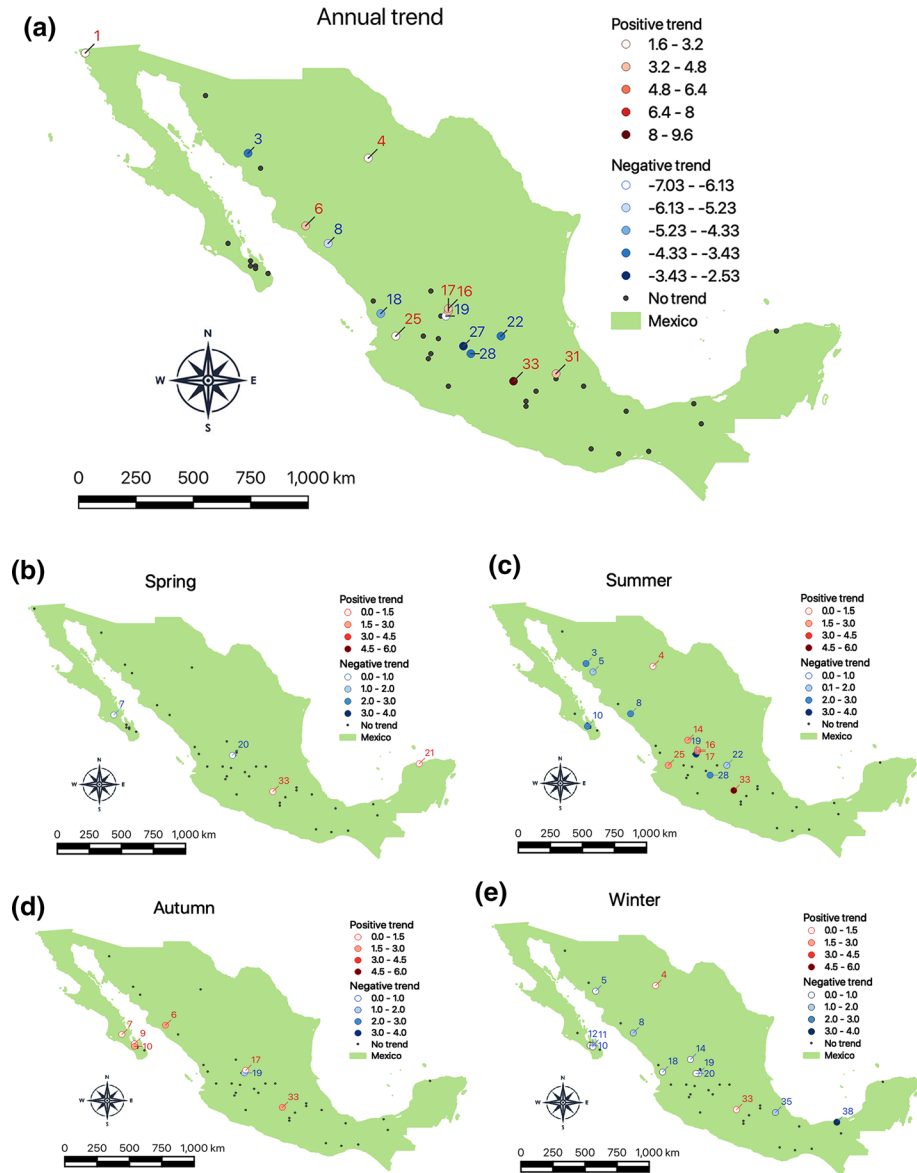


Fig. 3 Spatial distribution of the annual and seasonal precipitation trends from 1960 to 2010

the lowest availability of water and the highest population concentration in the country (CONAGUA 2018).

Seasonally, only two climatological stations had significant trends in the spring (Fig. 3b) at a 95% confidence level, and another two stations had trends at a 90% confidence level. Moreover, the summer (Fig. 3c) and the winter (Fig. 3e) showed 13 significant trends, but each had very different behavior because while there was an almost equal number of positive and negative trends in summer, the winter showed a marked negative trend throughout

the entire Mexican territory. Nevertheless, the negative trends observed during the summer were more important because this time of the year was when more than half of the annual precipitation was observed. In general, the behavior observed during the summer was more consistent with that observed at the annual level (Fig. 3a), which demonstrated the importance of this season in the annual rainfall regime. The observed trend behavior aligned with the obtained results by Méndez et al. (2008) for the same zones during the period from 1920 to 2004.

3.2 Behavior of the concentration index at annual and seasonal levels

The mean values of the concentration index at the forty-four stations at the annual level ranged between 0.084 and 0.265 (Fig. 4). These values aligned with the values observed worldwide by Monjo and Martin-Vide (2016). The extreme values observed annually were between 0.023 and 0.56, although the values higher than 0.42 are considered atypical (Fig. 4). The highest values were observed mainly in the north and northwest of the country at climatological stations 6, 7, 9, 11, 12, and 13, which showed values above 0.4. In these zones, the lowest annual quantities of precipitation were observed, suggesting that these regions were characterized by few rainy days per year and therefore by the possibility of the occurrence of extreme precipitation events.

In Fig. 5, the seasonal behavior of the concentration index from 1960 to 2010 is presented. In this figure, the distribution of the concentration values for each station is presented. It can be seen through the interquartile range and to the size of the whiskers that winter and spring were the seasons with the highest dispersion in the concentration index, while the autumn and summer showed the lowest values. In fact, the size of the upper whiskers shows that during the spring and winter, the distribution of the concentration values was not symmetrical, suggesting a right-skewed distribution.

The values for the concentration index in the winter and spring ranged from practically zero to almost 1. An example of these values was observed at station number 4, where the occurrence of only one event or two events with very different rain magnitudes during the complete season was common, causing high concentration index values, as can be

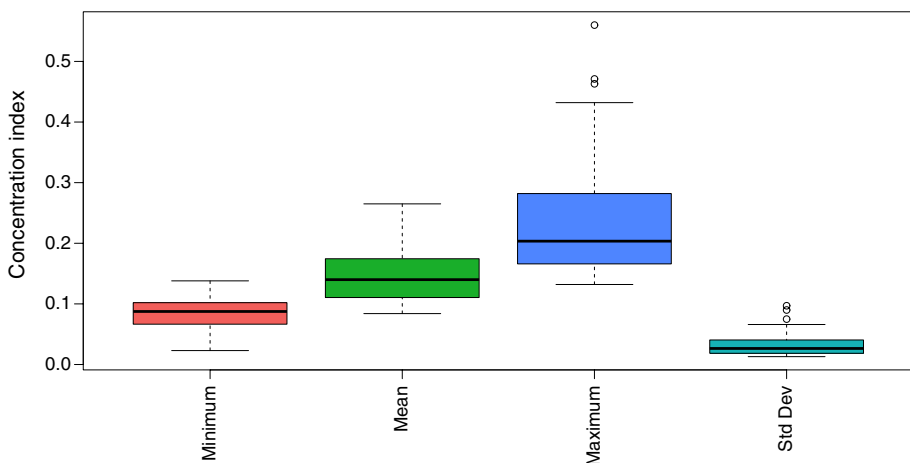


Fig. 4 Descriptive statistics of the concentration index at the annual level

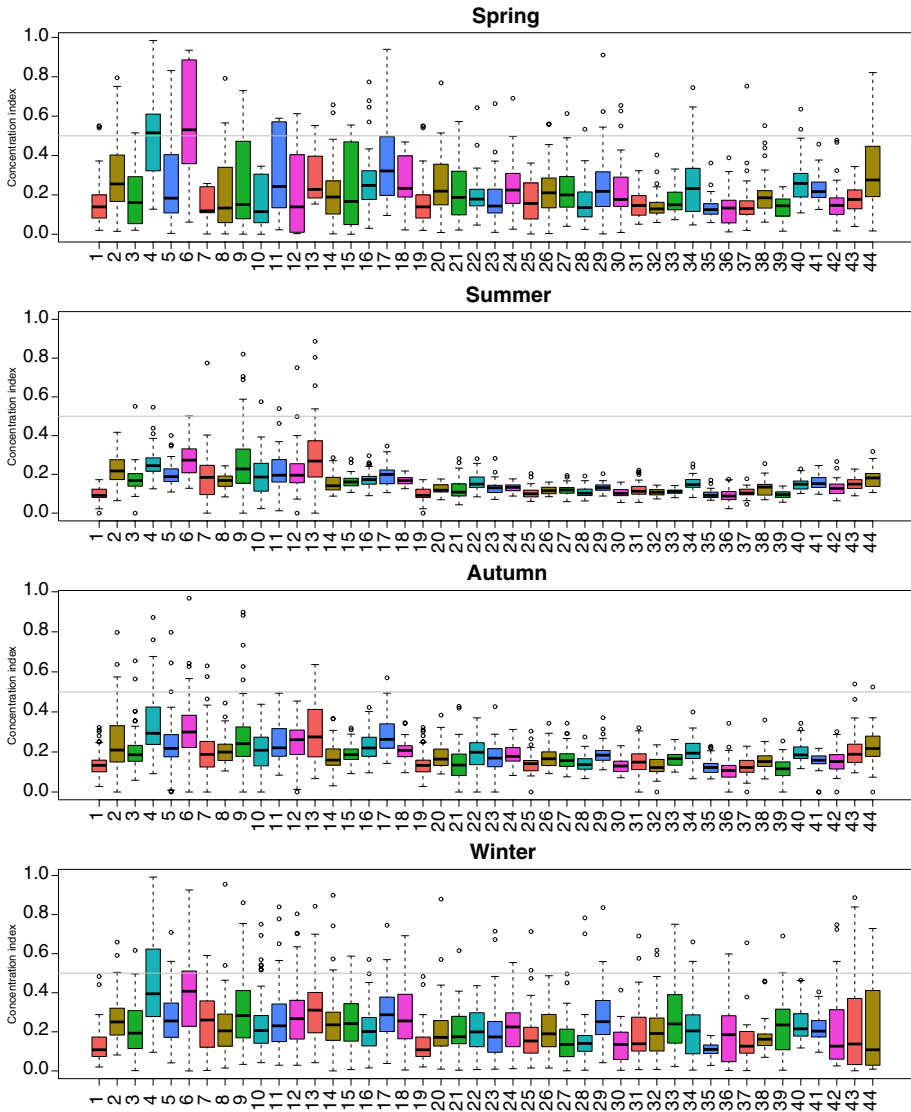


Fig. 5 Seasonal behavior of the concentration index from 1960 to 2010

appreciated upward in the second quartile. In contrast, low values, such as those observed in the first quartile, were associated with a few events of similar magnitude; this kind of value has been documented by Monjo and Martin-Vide (2016) to the east of the Sonoran Desert, where station number 4 is located.

Otherwise, the interquartile range for the summer showed a more condensed distribution of concentration index values in almost two-thirds of the climatological stations, with 50% of the concentration index values ranging from 0.023 to 0.346. These values were lower than those reported by Li et al. (2017) for China but were in agreement because, as has been pointed out in other studies, China has some of the most concentrated precipitation in

the world Núñez-González (2020). An exception to this trend occurred in the northern and northwestern regions where the concentration index values during the summer reached values higher than those mentioned previously for China, with values of up to 0.886. However, in these stations, most of the values greater than 0.5 were considered atypical (Fig. 5). In fact, the third quartile showed that at most stations, values higher than 0.4 were less probable. According to Monjo and Martín-Vide (2016), the high concentration could be linked to the rapid pace of physical processes, such as convection, in areas with a high degree of insolation. In fact, in their study, Monjo and Martín-Vide (2016) found high concentration values in regions in the west of the Sonoran Desert (northern Mexico). Moreover, the high concentration index values observed in the northern and northwestern regions, as well as the low quantities of rainfall that were observed in these regions by Li et al. (2017), could also be due to dry spells.

Figure 6 shows the spatial distribution of the observed trends for the concentration index at the annual and seasonal levels. At the annual level (Fig. 6a), nine positive trends were observed that were significant at the 95% confidence level, while there were four other significant negative trends at the same confidence level and one more at the 90% confidence level. The positive significant trends were distributed throughout the country. The highest concentration index trends were located in the northwest at climatological stations 3, 8, and 11 as well as in the southeast at station 38. Moderate trends were observed in the center and south of the country. Although the climatological stations with positive significant trends barely represented a quarter of the studied stations, the results suggested that in recent decades, precipitation has become more concentrated in the country. This trend could create risk since in the northern and northwestern regions, more dry spells can be expected, while in the center and south of the country, heavier rainy days can be expected (Li et al. 2017).

Seasonally, the autumn (Fig. 6d), spring (Fig. 6b), and winter (Fig. 6e) showed similar behaviors, with more significant negative trends than positive trends, although in the first case, there were six negative trends versus four positive trends. In the second case, there were four negative trends versus one positive trend; in winter, there were eight negative trends versus two positive trends. On the other hand, summer (Fig. 6c) showed a high number of positive significant annual trends. The spatial distribution of the significant trends at the seasonal level showed that negative trends were more common in the central and northern regions of the country during the four climatological seasons, while the positive trends were distributed all over the country. In the summer and autumn, the largest trends were distributed mainly in the northern region. An important trend that was observed during the four seasons of the year was at climatological station number 38, which was located in one of the rainiest regions of the country, specifically in the state of Tabasco, which historically has been exposed to flooding problems. According to Aparicio et al. (2009), in this region of the country in recent decades, flooding damage has increased due to a combination of population growth and urban settlement.

3.3 Relationship between the precipitation trend and the concentration index trend

The presence of positive trends for both precipitation and the concentration index could suggest risk because, as noted by Li et al. (2017), large amounts of precipitation and high concentration indexes indicate that heavy rains can be expected. In contrast, low precipitation and a high concentration index suggest that more dry spells could be observed. In the

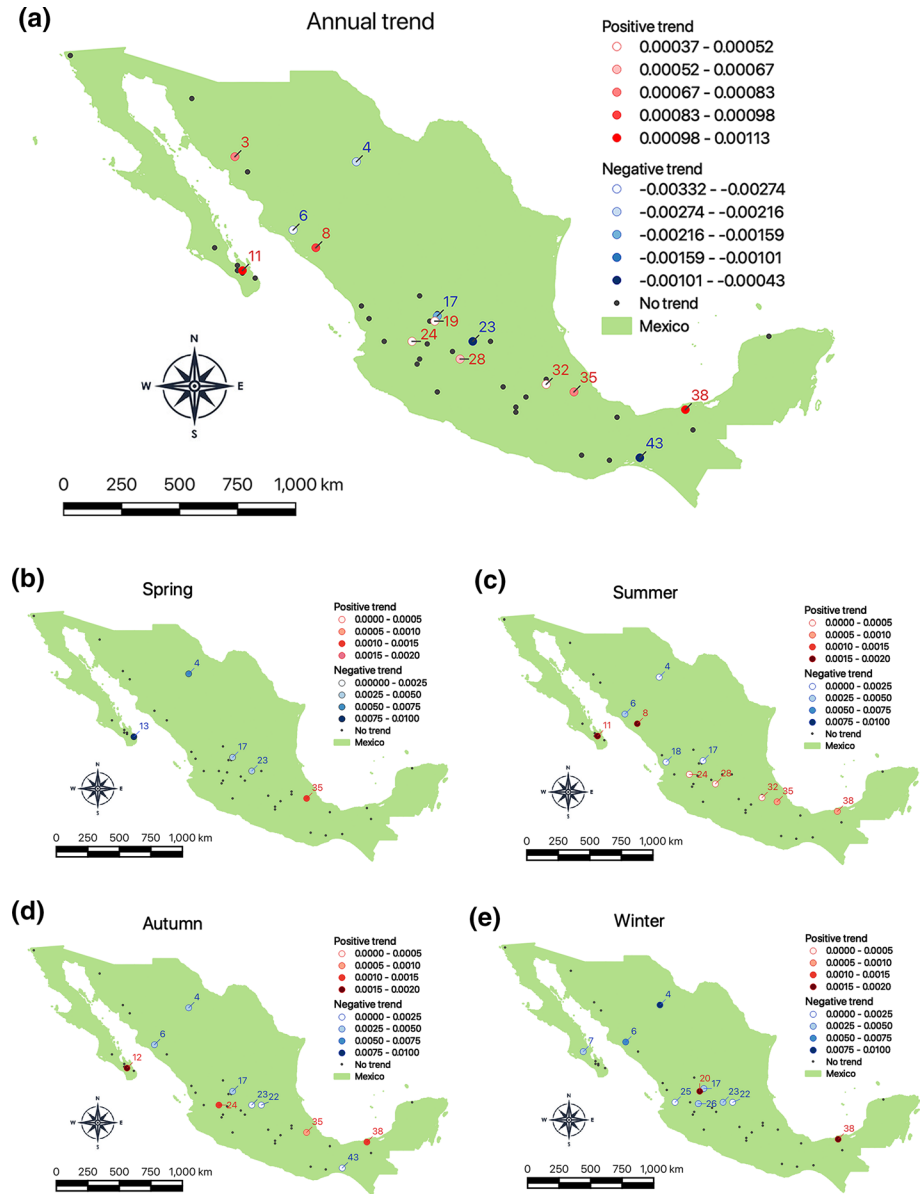


Fig. 6 Spatial distribution of the precipitation concentration trend from 1960 to 2010

results obtained for the trends of the precipitation and the concentration index, two types of relationships were observed. On the one hand, an increase in precipitation was observed, but the concentration index decreased. In contrast, the other type of relationship showed a decrease in precipitation accompanied by an increase in the concentration index. The first kind of relationship was observed at the annual level in the central and the northern areas of the country at stations 4, 6, and 17. Seasonally, climatological station number 17

shows this behavior in the summer and autumn, the time where the greatest amount of precipitation is observed, which suggests a more regular rainy season. On the other hand, station number 4 showed an increase in precipitation and a decrease in the concentration index during summer and winter, while station number 6 showed decreased values only in autumn. An increase in precipitation with a decrease in the concentration index did not seem to represent a risk because under these conditions, a more regular pattern of precipitation could be expected (Monjo and Martin-Vide 2016).

The second type of relationship, in which a decrease in precipitation accompanied by an increase in the concentration index was observed, was presented at the annual level at stations 3, 8, 19, and 28, all of which were located, as in the other case, in the central and northern regions of the country. At the seasonal level, during summer, two climatological stations in the northern and central regions (8 and 28) were observed to exhibit this kind of relationship. In winter, climatological stations 20 and 38, which are located in the central and southern regions of the country, also showed this kind of relationship. Contrary to the first kind of relationship, a decrease in precipitation accompanied by an increase in the concentration index can be considered a cautionary indicator.

On the one hand, stations located in the northern region could be considered potential droughts (Li et al. 2017) because the lowest quantities of precipitation were observed at these climatological stations. Additionally, because these stations are located near the Sonoran Desert, Monjo and Martin-Vide (2016) found high values according to several concentration indices. On the other hand, for the stations in the central and southern regions, it was necessary to perform a detailed analysis of the magnitudes observed in the concentration index trend because although the precipitation showed a decrease, these climatological stations were located in regions where the quantity of precipitation could be considered medium to high (CONAGUA 2018). Special attention was required for climatological station number 38 because although an increase in the concentration index was observed during the winter, this climatological station is located in a region where several problematic instances of flooding have been observed in recent years (Aparicio et al. 2009).

4 Conclusions

The trend of precipitation and its concentration at some stations in Mexico for the period from 1960 to 2010 was studied in this paper. On an annual basis, eight positive significant trends and seven negative significant trends were observed, with magnitudes ranging from 1.6 to 9.6 mm per year. An important decrease in precipitation was observed in the central and northwestern regions. The behavior observed during summer was consistent with that observed at the annual scale, which evidenced the importance of this season in the annual rainfall regime. The winter showed a marked negative trend throughout the country, which could be important in the northwestern region, where an important quantity of precipitation fell during this climatological season.

The concentration of precipitation was evaluated with an entropy-based index. At the annual level, the average of this index ranged between 0.084 and 0.265, although extreme values of up to 0.56 were observed. The highest values were observed mainly in the northern and northwestern regions of the country, where the lowest quantities of precipitation were also observed. Seasonally, the largest values in the concentration index were observed, especially during the spring and winter, when values of almost 1 were observed.

In summer, high concentration index values were observed mainly in the northern and northwestern regions, which could be associated with convective processes.

The trends of the concentration index at the annual level showed more significant positive trends than negative trends, suggesting that in recent decades, precipitation has become more concentrated. The highest values were located in the northwest of the country. Summer was the season with most positive significant trends.

According to the trends of precipitation and the concentration index, two types of relationships were observed. One was characterized by an increase in precipitation but a decrease in the concentration index, and the other was characterized by a decrease in precipitation accompanied by an increase in the concentration index. The first case did not seem to represent risk because the described conditions were indicative of a more regular precipitation pattern. However, the second case could be considered a cautionary indicator, especially in the northern region, where it could suggest the potential for drought.

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Code availability The code used for the calculation of the concentration index could be available under request. Trend methods are highly known.

Data availability Data used in this research are available through the National Meteorological Service of Mexico web page at: <https://smn.conagua.gob.mx/es/informacion-climatologica-por-estado>.

Compliance with ethical standards

Conflict of interest The author declares that they have no conflict of interest

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