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Variability of rainfall regimes in Central Mexico, 1961-2008

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Abstract General rainfall trends are analysed in Central Mexico for the period of time 1961-2008. The region has three different divisions: the nearctic and neotropic biogeographical regions and the band limit between them. This fact along with the physiographic characteristics of the location of the 21 meteorological stations used for the analysis determine the rainfall regimes variability. We implemented a criterion to numerically determine the onset and demise of the rain season. We analysed time dependent tendencies of total annual precipitation, onset, demise, duration and intensity of the rain season. There is a variability of rainfall in the studied area which is described in detail. We made attempts to rationalise the variations as functions of altitude, latitude and location relative to the biogeographical regions and we found that all these variables allowed us to clearly define three regions. Possible effects of climate change on the variability found are only detectable when the three regions are separately analysed.

Keywords Rainfall variability · Central Mexico

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1 Introduction

Considering the significance of a precise knowledge on the consequences of global warming in climate change it becomes important to study local rainfall variability among other climatological variables. The Intergovernmental Panel on Climate

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Change (IPCC) has foreseen consequences that go from increase in precipitation in some places to draughts in some others. Therefore it is of vital importance to know how regional climate variability behaves in order to be able to determine both short-term and long-term climate change scenarios for a given region. What has been anticipated is that very likely precipitation will increase in high latitudes and will decrease in most subtropical land regions, continuing with the recently observed trends.

Central Mexico is on a transition zone between the nearctic and neotropic biogeographic provinces, see Fig. 1. The region concides with the transition zone between the southern mountain systems and the Mexican highlands therefore we divided this region into the followingf three subregions: Mexican Volcanic Belt (MVB), Southern Sierra Madre (SSM) and the transition zone (TRANS) between them. The knowledge of climate variability in this zone is of extreme importance both for local decision-making and for global understanding of climate change. This knowledge should be very important in topics like water resources and all the concomitant effects of its availability.

In this paper we report variability of rainfall regimes in central Mexico based on meteorological data bases for the period 1961-2008. Even though the transition zone between the nearctic and neotropic biogeographic provinces is quite large, we concentrate on the region shown in Fig. 1 for two reasons: i) the availability of data, and ii) the aim of mexican authorities to regionalize this sort of studies. We first preclude the possibility of having influences of solar cycles and of phenomena like El Niño or La Niña and then base our analysis on the tendencies of total and seasonal precipitation, onset, demise and duration of the rain season. In the course of our analysis we provide a refined mathematical criterion to decide when the rain season formally starts and formally ends.

2 Data analysis

2.1 Study area and data

Daily precipitation data from twenty-one meteorological stations in central Mexico, covering parts of the states of Mexico, Guerrero, Puebla, Morelos and the Federal District were used for the analysis. Information was obtained from the following sources: Meteorological Monitoring Network of the National Water Commission, National Meteorological Service and ERIC-II database for the period of time 1961 to 2008. Altitudes in the region go from 666 m in the south to 5500 m above the sea level in the Popocatepetl volcano, however stations cover an interval that goes approximately from 750 m to 2850 m above sea level. This along with the existence of three physiographic provinces and the completeness of daily observations supplied the criterion to select the stations. Table 1 summarises general information on selected stations. Each physiographic province has its own dominant ecosystem: coniferous evergreen forests in the MVB, tropical deciduous forest in the SSM and crop fields and the largest urban areas in the valleys of the transition zone.

Data quality was verified with R-ClimDex program [9]. Bad data were removed from the data base and missing data were not replaced or estimated. Even though in this region there are more than 120 meteorological stations only 21 of them satisfied the requirements of the quality control.

Fig. 2 shows the typical annual distribution of the rain during a year for a representative station in each province within the analysed region; the figure also shows the time series for the total annual precipitation in the studied period (1961-2008). Note that the behaviour in the MVB does not follow the pattern shown by the TRANS and SSM in the sense that there is not a local minimum during the season but a sustained high precipitation. Given precipitation data in the region, one concludes that it may rain any time in the year but that there is a proper rainy season which roughly occurs between the months of May and October. The descriptive statistics of the data used in the analysis shows that the average annual precipitation in the region was 971 mm with a standard deviation of 275 mm; the median was 923 mm, and the maximum, and minimum annual precipitations were 2485 mm (Miacatlan station, 17006) and 445 mm (Ameca station, 15094), respectively, for the period 1961-2008. The asymmetry is 0.52, indicating a longer tail to the right of the central maximum of the distribution, and the kurtosis is 6.55. High kurtosis indicates the presence of values far from the mean and confirms a high heterogeneity in the region. The null hypothesis of a normal distribution for the precipitation is confirmed by the usual tests and coincides with previous studies in approximately the same region. [4]

Not all the stations have the same amount of information, *i. e.* the number of years with sufficient information during the rainy season to justify their inclusion in the analysis varies from a minimum of 31 years (Tlacualera station, 17021) to a maximum of 48 years (Cuautla station, 17005 and Ticuman station, 17018); the average number of years with information for the 21 stations is 42.1 years (standard deviation of 4.47 years) in the 48 years period.

2.2 Detection and analysis of trends

In order to be able to detect any trend that could be related to climate change due to global warming, one has to eliminate all known possible influences on the behaviour of time series. To explore the possibility of the precipitation time series being influenced by the eleven-year solar cycle, we calculated the power spectral density functions of a number of time series of different stations for both rainy and dry months. The results show that the cycles that can be seen on the time series have a period of approximately 20 years and have no apparent relationship with solar cycles. A time series of the Southern Oscillation Index (SOI) was obtained [8] and Fourier analysed to find the most probable frequencies of occurrence of El Niño and La Niña phenomena, finding that a period of around 5.5 yr can be assigned for the analysed period of 134 years, from 1876 up to date. As for the case of the solar cycle, the power spectral density function, obtained through the Fourier transformation of the autocorrelation function, showed no apparent relationship between the precipitation time series and either El Niño or La Niña phenomena. Fig. 3 shows the behaviour of these phenomena along with data from two stations in the frequency domain.

Considering that it may rain any time in the year, we therefore had to distinguish between the proper rainy season and rains out of season, some of which are caused by hurricanes and/or tropical storms both in the Caribbean/Gulf of Mexico and the Pacific Ocean regions.

The first problem one faces in the analysis of the precipitation time series is the need to establish criteria that allow a numerical characterisation of a rainfall period and a rainy season. Numerically a proper rainy season is a collection of successive rainfall periods. Thus we used two complementing criteria. The first one detects and counts days in which rain is recorded, this we call a rainfall period, and takes into account all events, even if they are only a drizzle of a few minutes in just one single day. Then it measures the time along a given year in which the succession of such events occurs using the second criterion that aims at detecting the proper rainy season.

The rainy season is detected through the following criterion which has been widely used; see for example [6]. We calculate the time series given by

$$S_k = \sum_{i=1}^{k} (p_i - \bar{p}), \qquad k = 1, \ldots, N, \tag{1}$$

where p_i is the amount of rain on the i-th day, N is the number of days of the year, and

$$\bar{p} = \frac{\sum_{i=1}^{N} p_i}{N}$$

is the daily average amount of rain for the year.

From one day to the next, this succession will either decrease if the amount of rain on that day is below the average, or increase if the amount of rain on that day is above the average.

Thus the rainy season will start when the general tendency of the function $\{S_k\}_{k=1}^{N}$ stops decreasing and starts increasing and it will demise when the tendency stops increasing and goes back to a sustained decreasing tendency.

Since this criterion is mainly visual and therefore quite subjective, we developed a complementary algorithm for determining the onset and demise of the rain season that gathers additional information from the time series. First, the critical points were located (i. e. where there is a change of sign on the slope) of the graph of $\{S_k\}_{k=1}^{N}$. Next, from the set of critical points three main minima were chosen (whose indexes of days we will call $m_1 < m_2 < m_3$) and three main maxima ($M_1 > M_2 > M_3$). Then, for the minima we calculate the distance between the value of S on each of them and τ_o days later:

$$d_{m_i} = S_{i+\tau_o} - S_i$$

$i = m_1, m_2, m_3$, whilst for the maxima we calculate the distance between the value of S on each of them and τ_d days later:

$$d_{M_i} = S_{i+\tau_d} - S_i$$

$i = M_1, M_2, M_3$. Finally, we chose the onset of the rainy season as the day m_i such that its corresponding distance, d_{m_i}, is greater than the corresponding distances of the other two minima. Analogously, the demise date is the day M_i such that its corresponding d_{M_i} is smaller than the corresponding distances of the other two maxima. We established these criteria because the change of sign of the slope of $\{S_k\}_{k=1}^{N}$ is a necessary condition but it is not sufficient to establish neither the onset nor the demise of the rainy season. Therefore the sufficiency is given by the fact that one is not facing an isolated rain event but at the general trend.

Fig. 4 shows a typical plot of expression (1). The leading periods of τ_o and τ_d in the previous expressions were empirically determined to be 7 and 10 days, respectively, based on field observations and numerical calibration of the algorithm; the previous determination of what we are calling rainfall periods, was of great help in measuring these lengths. If this criteria are to be used in regions with different rainfall regimes the values of τ_o and τ_d should be specifically determined.

The results of the application of the first criterion are shown in Fig. 5 where a group of three representative stations is shown for every province. Every rainy period in a given year is indicated with a vertical line whose length specifies the number of days of that period. The application of the second criterion is shown in the same figure. The vertices of the broken lines indicate the beginning and the end of the rainy season. In this way we obtained two time series associated to the rainfall which are the starting and ending time series for the season. These series were then processed to find their tendencies along the 1961-2008 period. These tendencies are represented by the straight lines, obtained as linear regressions, in the same figure. The change in the onset and demise dates of the rainy season is analysed in conjunction with the amount of rain and the number of rainy days of the season. This allows for an easy detection of the increase of torrential rains during the year. This increment could be due to a longer rainy season, a higher amount of rain or both.

Linear regressions were also made for four other time series: the annual precipitation, P_T, the amount of rain of the season, P_S, the number of days of the season, D, and the ratio of those two, I, which constitutes a measure of rain intensity. Linear regressions were calculated with two different methods in order to make sure that points with large deviations from the mean values were not biasing the determination of the slopes. The first one minimises the absolute deviation (MAD) whereas the second one minimises the chi-squared distribution, χ^2 [7]. The results show almost equal values for the two approaches, indicating that regressions are independent of the calculation method even though MAD is supposed to be a robust method as compared to the chi-squared one. Table 2 shows a summary of results obtained from linear regressions which are discussed in the following sections.

3 Results and discussion

As it was mentioned earlier, the geography of the analysed region is characterised, among other things, by a strong gradient in altitude, from 5500 m above sea level in the northeast to 666 m in the south, and encompasses three physiographic regions: the Mexican Volcanic Belt, the Southern Sierra Madre and the transition zone between them. According to the graphs in Fig. 5 and the data in Table 2, we found that the rainfall in the analysed stations during the 42.1 years average in the 1961-2008 period has followed a behaviour related to the particular biogeographical province of each station, see Fig. 1. Table 2 shows the results of the analysis of variability of total precipitation, ΔP_T, precipitation in the rainy season, ΔP_S, duration of the rainy season, ΔD, intensity, ΔI, onset Δo and demise Δd of the rainy season. These results clearly show that there is a distinctive behaviour in each one of the regions.

Total precipitation. Total annual precipitation increases in all but seven stations (Ameca, Cuautla, Chietla, Huautla, Iguala, Huitzuco, and V. Trujano) along the averaged 42.1 years analysed, as can be seen from column ΔP_T of Table 2. In Ameca and Cuautla stations the negative variation, meaning a decrease of P_T, is probably due to the growth of the urban zone. In Chietla, Huautla, Iguala, Huitzuco, and V. Trujano stations, all in the Southern Sierra Madre zone, the decrease of P_T cannot be ascribed to human activities, except in the city of Iguala. Comparing columns ΔP_T and ΔP_S it is evident that most of the total precipitation occurs during the rainy season.

The changes detected trough our analysis may be confirmed using the displacement of the functions describing the probability density for each one of the almost five decades in the studied period (or by the 10/90 percentile ranges). Fig. 6 shows two cases: the increasing tendency for Ticuman station (upper panel), and the decreasing tendency for Cuautla station (lower panel).

Onset of rainfall season. Regarding the onset of the rainy season, we note from columns Δo and Δd in Table 2, that the onset has undergone an average delay of six days in the Volcanic Belt, extreme values are one (Cuernavaca) and nineteen (Ameca) days in the analysed period. A slighter average delay of five days in the transition zone, from 0.3 (Yautepec) to 12.3 (Cuautla) days (Cuautla station located in a valley with strong agricultural activity and growing urban areas), and a mixed behaviour in the Southern Sierra Madre: five stations show an average earlier onset of 5.5 days while the other three (Chietla, Huitzuco, and V. Trujano) show an average delay of 1.5 days (Note the 11.5 days earlier onset for Tlacualera station). From this analysis we can conclude that at the end of the studied period the rain season is starting earlier than in 1961 in the SSM by almost three days, while it has been delayed in the transition and MVB regions by five and six days, respectively.

Demise of rainfall season. The end of the rainy season shows more variability than the onset. In the north or MVB, the tendency is towards a delay of the end of the season by an average of 3.7 days with the exception of Atlatlahucan which has a tendency to end sooner by 5.2 days; the largest delay, 10.8 days, occurs in Tlacotepec. In the transition region five stations show a tendency of the season to end earlier by 3.6 days and three stations show a tendency to a delayed end by 2.9 days. In the south, the tendency is towards a delay of the end of the season by an average of 9.5 days (5 stations) but three stations show a tendency for the end to occur 5.7 days earlier; the largest delays occur in Chietla and Huautla stations, where the delay has reached almost 16 and 17 days, respectively. Thus, the result is that the season is ending sooner than in 1961 in the transition region by a day and ending later by four days in the MVB and in the SSM.

Duration of rainfall season. The duration of the season along the analysed period shows a slight increment of around 7.5 days in Huitzilac, Cuernavaca and Tlacotepec stations, and a decrease of around 16 days in Ameca and Atlatlahucan stations, all in the MVB (Table 2). Thus, one could conclude that there is an almost constant duration for the rainy season in the fraction of the Mexican Volcanic Belt included in the study. On the other hand the transition zone shows more variability including decrements of 7.8 days in average in Yautepec, Cuautla, Temilpa, Miacatlan, and Zacatepec, and almost no variation (2.5 dyas) in Temixco, Ticuman, and Tepalcingo. The SSM shows a distinctive behaviour: the duration of the season has increased for 5 stations by an average of 13.4 days (high increments in Huautla and Xicatlacotla with more than 18 days), two stations where no change is detected (Huitzuco, 0.6 days increment and Iguala, 0.7 days decrement), and only V. Trujano station having a decrement of 6.3 days. Thus, the duration of the season has increased by seven and a half days in the SSM, and has decreased by one day in the MVB and by six days in the transition region.

Intensity. The extreme values indicate that Miacatlan station in the TRANS region, and Tlacualera in the SSM, show an increase of 2.3 mm/day during the analysed period, while Huautla station in the SSM shows a decrement of 2.9 mm/day during the same period. The general behaviour at the Volcanic Belt is as follows: Huitzilac, Cuernavaca, and Tlacotepec stations show much heavier rainfall (average of 207.7 mm) over a slightly longer period of time (7.5 days in average) which means an increase in intensity (27.7 mm/day); while Ameca and Atlatlahucan show a modest decrement in rainfall (48.7 mm in average), the season tends to be shorter (by an average of 16 days), and thus intensity in the whole of the MVB region still increases by 3 mm/day. The stations in the transition zone show a rain increment of 116 mm in average (including Cuautla station which shows a decrement of 137.4 mm) and a reduction of the season by an average of 5.9 days, causing an increase in intensity of 1.1 mm/day. The stations in the SSM can be classified in two groups: the first one formed by Tlacualera, Huajintlan, Chietla, and, Xicatlacotla, shows an increase in intensity (0.7 mm/day) due to heavier rainfalls (141.8 mm) over longer periods of time (11.9 days). The second group is constituted by Huautla, Iguala, Huitzuco, and V. Trujano stations which show rain patterns with decreasing intensity (-1.3 mm/day) due to lighter rainfall (-101.3 mm) over slightly longer periods of time (3.3 days). The intensity in the SSM has slightly decreased, indicating that the daily average rain has increased and almost compensated for the longer season. The intensity in both, the MVB and the transition regions has slightly increased. This increment is probably due to the shorter season in both regions and a slight increment in the daily average.

There are local variations in the three physiographic regions that could mask the effect of climate change on a particular station. These variations are due to a number of factors such as the fact that the analysed region is in the border between the nearctic and neotropic biogeographic provinces. This border is not a line but a wide transition band which coincides with the physiography of the region and therefore with its major climatic features. Other factors producing the observed variability include heat-island effects in the cities of Cuautla, Cuernavaca and Iguala, and the high rate of change of land usage all over the region. The main changes are deforestation in the northern part of the region, agricultural to urban usage in the transition zone and deforestation in the south. A particular example is the city of Cuernavaca, that has grown from around 145,000 to 365,000 inhabitants between 1960 and 2010, and its neighboring towns that are nowadays part of the metropolitan zone of Cuernavaca adding up to 875,598 people [10].

We found, however, that there is a clear tendency as a function of altitude and latitude in the whole region with high precipitation and intensity values in the north and low values in the south. Fig. 7 shows a plot of the variation of total precipitation, ΔP_T, versus altitude for the twenty-one stations studied and for the whole period of time with data availability. As it can be seen from Fig. 1 and Table 2, this tendency is also a function of latitude. Huitzilac station, in the north, is one of the stations with a larger increment in total annual precipitation, whereas Huautla and V. Trujano stations, more than 50 km to the south of Huitzilac, show the larger decrease of P_T.

The sequence Huitzilac, Cuernavaca, Temixco, is also north-south and the tendency of ΔP_T is to diminish as a function of altitude as well as towards the south. In the transition zone, Temixco, Yautepec, and Zacatepec have similar behaviours. Their shift from the expected tendency due to the global climate change regarding the latitude change may be caused by the local variations described above. In this graph Cuautla station appears as a special case, off the general tendency, as mentioned before, possibly because of the extreme alteration of the environment derived from the city growth. It is worth mentioning at this point that this is not the case with the city of Cuernavaca because a large part of Cuernavaca is on a glacis that absorbs and releases rain water and serves as a heat radiator.

An ANOVA analysis of duration of rainfall season upon grouping the stations according to the biogeographic provinces yields significative differences with $p = 0.02$. This means that the three groups in which we have divided the region under study are statistically correct and therefore rainfall variability can be regarded as dependent of regional characteristics as well as global circulation models. Thus, we obtained that, in average, in Central Mexico the rainfall season in the MVB zone shortens by around 1 day, in the SMM zone lengthens around 8 days and in the transition zone shortens by around 6 days as can be seen from the summary shown in Table 2. One remarkable result is that the average of rainfall season duration in the whole region under study is almost equal to zero (-0.02 days). If we would suppose that the variability we observe were due to global climate change, it would be misleading to consider this region as a homogeneous whole. However the subregion variability, could be very well be ascribed to climate change under this supposition. These results are important given that agricultural cycles and economic activity are affected by this variations in the duration of the rainfall season and also should be taken into account if adaptation actions were to be taken.

Another way of classifying the information obtained from the meteorological stations is by constructing an histogram according to the change in total precipitation, ΔP_T. Fig. 8 shows this classification on the map of the region under study. One would expect that this classification would yield disjoint regions on the map, however there are singularities due to particular local conditions for some stations. As it can be seen from Fig. 8 there is some correlation between the intervals of the histogram and the latitude, which in this case has also some correlation with altitude. On the south there is a region in which ΔP_T is negative, in the transition zone ΔP_T is positive, and in the north, that is to say Cuernavaca and Huitzilac stations, there is the greatest increase in total precipitation. The singularities are Huautla station which has a $\Delta P_T = -242.57$ mm although it is in a region where ΔP_T values are within the interval $(0, 160)$ mm, the area where the station is located has been altered by agricultural activities and the tropical deciduous forest has disappeared. The other two singular stations are Cuautla and Ameca for which ΔP_T is negative although they are within regions where one should expect positive values. The explanation of these singularities is that both Cuautla and

Ameca are highly populated and growing urban conglomerates that are acting as heat islands.

The existence of these singularities precludes the possibility of generalising the variability behaviour through an interpolation that would include all stations. Excluding the three singular stations however, it is possible to interpolate the data via a CoKriging method and generalise the variability in the analized region (Fig. 9).

The general tendency of regional climate variation for the analysed region given by general circulation models yields a decrease of total precipitation of 27 and 81 mm for the years 2020 and 2080, respectively [1]. On the other hand, in the analysed stations the variability goes from -242.57 to 318.27 mm (see Table 2) for the analysed period (42 years average). The general tendency should be the resultant of the combined local effects. However, if we extrapolate the local data from the stations to the years 2020 and 2080 and average the results, our estimations do not coincide with those of the general circulation model. Therefore global models should be taken with care if one wants to assess the climate change in a specific area and linear extrapolation of tendencies from specific stations to estimate large region climate change should also be examined. In other words these results pose, once more, the problem of downscaling and upscaling of meteorological data as an issue to be taken into consideration.

4 Conclusions

In this study we analysed rainfall variability in central Mexico. The onset and demise of the rain season were determined with an improved algorithm that avoids subjective determinations. Indications of the influence of climate change on rain appear in our analysis –an increment of total precipitation, as well as distinctive changes in the intensity and duration of the rainy season.

Variability of rainfall regimes can be individually characterised considering all the effects due to the location of each station within the analysed region in central Mexico, that is to say, factors like the fact that most of the region is in the transition zone between the nearctic and neotropic biogeographical regions, or the fact that the altitude of the stations covers a very large range. Therefore, local physiographic characteristics have to be accounted for in any local climatic analysis. However the tendency foreseen by the IPCC [5] is evident from Fig. 7. We made an attempt to upscale our results on local tendencies to compare them with a general circulation model estimates but upscaling is more complex than linear extrapolation and averaging. More work has to be done in order to match the two approaches: global circulation model downscaling and local data upscaling.

It is important to study local changes in climate in order to find out the global change effects in a given location. From the results we obtained it is evident that regionalisation may lead to the conclusion that there are no changes at all. However the analysis of data station by station shows that there are considerable effects in very small regions.

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References

1. Bolongaro-Crevenna, A., Sierra, R., Torres, V., Márquez, A., Ramírez, J., Uribe, S., Castillo, F., Lagunas, R., Suárez, F., Sotelo, N., Velasco, B., Monsalvo, C.: Diagnóstico del impacto y riesgo derivado de la variabilidad climática y el cambio climático global en la disponibilidad y manejo del agua y en la agricultura. Instituto Nacional de Ecología, México. Avaliable online at http://www.ine.gob.mx/descargas/cclimatico/e2006c.pdf (2006)
2. Deutsch, C.V., Journel, A.G.: Geostatistical Software Library. Oxford University Press. (1998)
3. Dewes, C., Gautier, C., Jones, C., Eakin, H., Carvalho, L.: Trends in rainy season characteristics over Mexico. American Geophysical Union, Fall Meeting 2009. (2009)
4. Estrada, F., Martínez-A., A., Fernández-E., A., Luyando, E., Gay, C.: Defining climate zones in méxico city using multivariate analysis. Atmósfera **22(2)**, 175–193 (2009)
5. IPCC: Climate Change 2007. The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K. B. Averyt, M. Tignor, H. L. Miller (eds.) Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 996 pp. (2007)
6. Liebmann, B., Marengo, J.A.: Interannual variability of the rainy season and rainfall in the brazilian amazon basin. J. Climate **14**, 4308–4318 (2001)
7. Press, W.H., Flannery, B.P., Teukolsky, S.A., Vetterling, W.T.: Numerical Recipes (Fortran). Cambridge University Press (1989)
8. SOI: Southern Oscilation Index, Australian Bureau of Meteorology, National Climate Centre. Available online at http://www.bom.gov.au/climate/current/soihtm1.shtml (2009)
9. Zhang, X., Feng, Y.: RClimDex (1.0). Climate Research Division, University of Victoria, Canada (2004)
10. INEGI: Resultados preliminares del censo 2010. Instituto Nacional de Estadística, Geografía e Informatica. INEGI (2010).

Table 1 General information on the twenty-one selected stations.

Name	*Number*	*Province*	*Altitude*	*Latitude N*	*Longitude W*
Ameca	15094	MVB	2450	19.19	-96.87
Huitzilac	17047	MVB	2850	19.06	-99.27
Atlatlahucan	17001	MVB	1656	18.94	-98.93
Cuernavaca	17004	MVB	1529	18.92	-99.24
Tlacotepec	17020	MVB	1302	18.81	-98.75
Yautepec	17024	TRANS	1150	18.87	-99.08
Temixco	17014	TRANS	971	18.85	-99.23
Cuautla	17005	TRANS	1309	18.80	-98.95
Ticuman	17018	TRANS	1130	18.76	-99.12
Temilpa	17013	TRANS	1000	18.71	-99.09
Miacatlan	17006	TRANS	1200	18.70	-99.29
Tepalcingo	17015	TRANS	1200	18.67	-98.89
Zacatepec	17026	TRANS	1226	18.65	-99.18
Tlacualera	17021	SSM	1560	18.62	-98.93
Huajintlan	17007	SSM	1049	18.55	-99.35
Chietla	21024	SSM	1222	18.53	-98.58
Xicatlacotla	17033	SSM	1000	18.45	-99.10
Huautla	17008	SSM	971	18.43	-99.03
Iguala	12116	SSM	751	18.35	-99.55
Huitzuco	12115	SSM	940	18.30	-99.33
V Trujano	12093	SSM	842	18.30	-99.48

Table 2 Variability of rain season (1961-2008). Negative (positive) values indicate earlier (later) dates in the cases of onset, o, and demise, d, of the rain season and reduction (increase) in the case of total annual precipitation, P_T, season precipitation, P_S, duration, D, and intensity, I, of the rain season. Values reported are those calculated with MAD method.

Name	*Number*	ΔP_T	ΔP_S	ΔD	ΔI	Δo	Δd
		mm	*mm*	*days*	$\frac{mm}{day}$	*days*	*days*
Ameca	15094	-83.03	-79.72	-19.27	-0.12	19.07	0.52
Huitzilac	17047	316.88	275.87	8.87	1.43	2.03	4.96
Atlatlahucan	17001	10.13	-17.72	-12.82	0.61	10.42	-5.22
Cuernavaca	17004	229.67	227.90	5.90	1.25	0.55	6.06
Tlacotepec	17020	82.75	119.45	7.71	0.47	3.00	10.79
Average	MVB	121.96	115.95	-0.92	0.77	6.42	3.75
Yautepec	17024	127.43	106.66	-6.40	1.10	0.26	-6.65
Temixco	17014	157.88	158.94	-4.45	1.36	1.28	-3.40
Cuautla	17005	-153.24	-137.37	-9.35	-0.71	12.35	3.03
Ticuman	17018	262.12	245.64	-3.12	1.97	0.76	-2.19
Temilpa	17013	171.85	136.48	-6.65	1.27	8.58	1.95
Miacatlan	17006	271.31	224.51	-9.81	2.27	7.35	-2.40
Tepalcingo	17015	123.10	147.98	0.04	1.01	5.63	3.75
Zacatepec	17026	56.66	57.85	-6.86	0.66	3.58	-3.25
Average	TRANS	125.59	116.05	-5.89	1.11	4.91	-1.25
Tlacualera	17021	318.27	294.83	6.46	2.29	-11.48	-4.91
Huajintlan	17007	94.71	154.89	9.19	0.71	-2.76	8.11
Chietla	21024	-40.90	19.57	13.85	-0.38	2.24	15.69
Xicatlacotla	17033	84.21	98.09	18.23	0.07	-8.50	5.19
Huautla	17008	-242.57	-204.63	19.47	-2.87	-2.38	17.09
Iguala	12116	-41.68	-32.14	-0.72	-0.21	-2.47	-3.26
Huitzuco	12115	-72.24	-52.20	0.61	-0.37	0.37	1.43
V Trujano	12093	-171.21	-116.16	-6.34	-1.59	1.77	-8.83
Average	SSM	-14.41	15.66	7.51	-0.33	-2.75	3.86
Total average		75.79	80.94	-0.02	0.52	2.59	1.73

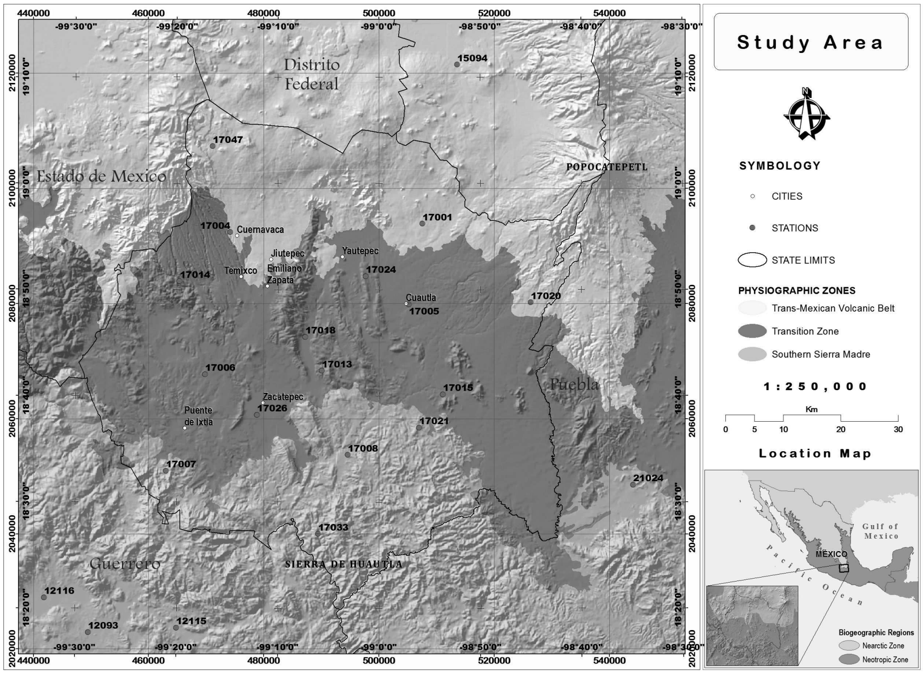

Fig. 1 Nearctic and neotropic biogeographic provinces and the transition zone between them. The inset shows the location of the analysed region in central Mexico.

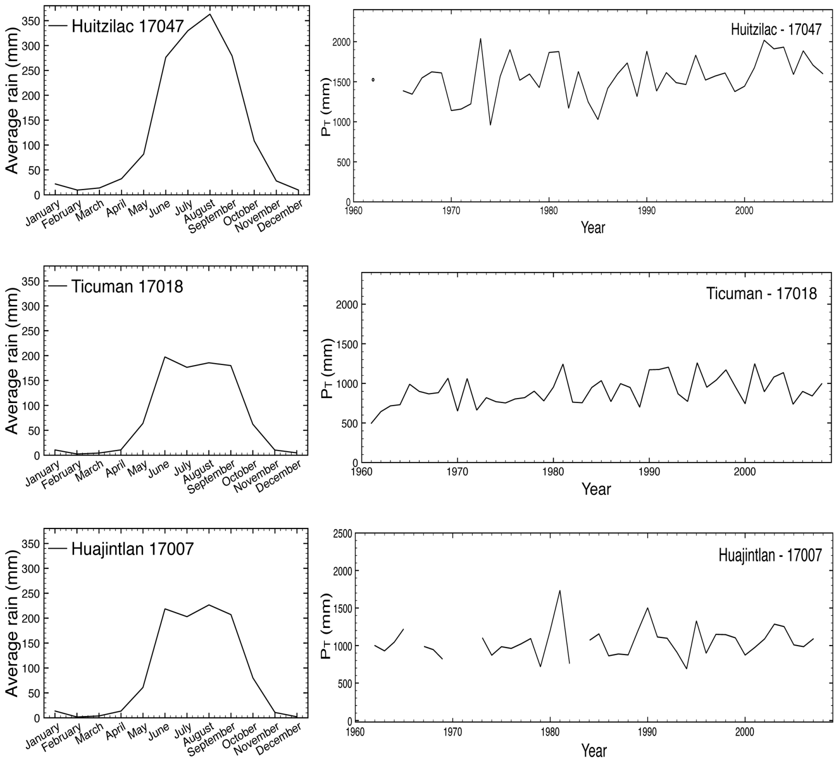

Fig. 2 Typical annual distribution of the rain during a year for a representative station in each province within the analysed region; the typical behaviour is obtained by averaging the daily rain within each month for the years in the studied period (1961-2008). Right panels show the time series for the total annual precipitation in the same period.

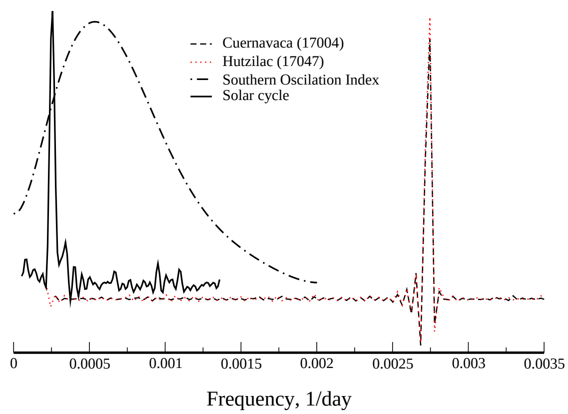

Fig. 3 Frequency domain data of SOI, solar cycle and precipitation of stations Cuernavaca - 17004 and Huitzilac - 17047.

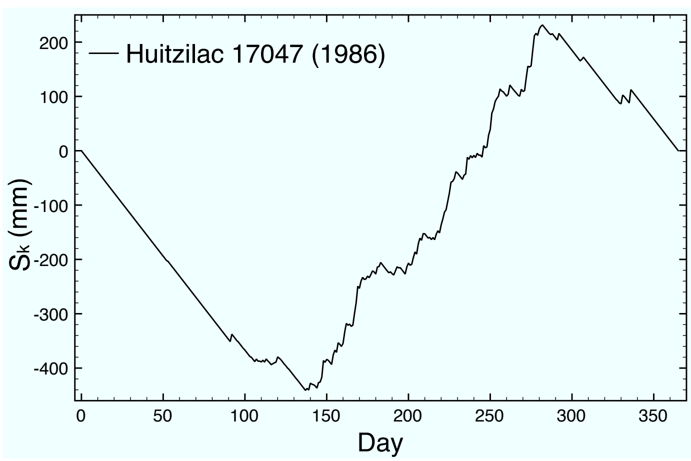

Fig. 4 Plot of $\{S_k\}_{k=1}^{N}$ for 1986 on station Huitzilac - 17047.

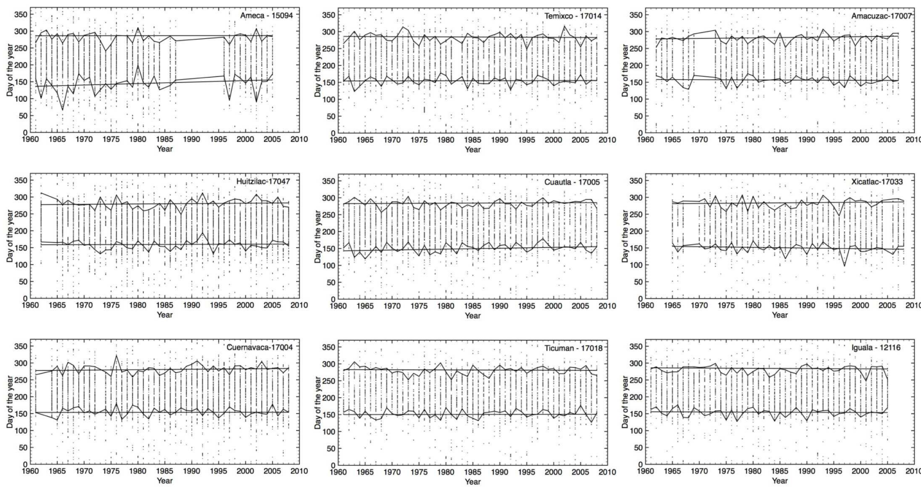

Fig. 5 Rainy seasons for the analysed period (1961-2008). Graphs in panel show results of the criteria used for the beginning and end of the annual season. Straight lines indicate the linear fit to the data. Other rainy periods and their duration are shown as vertical lines outside the season, either before or after it.

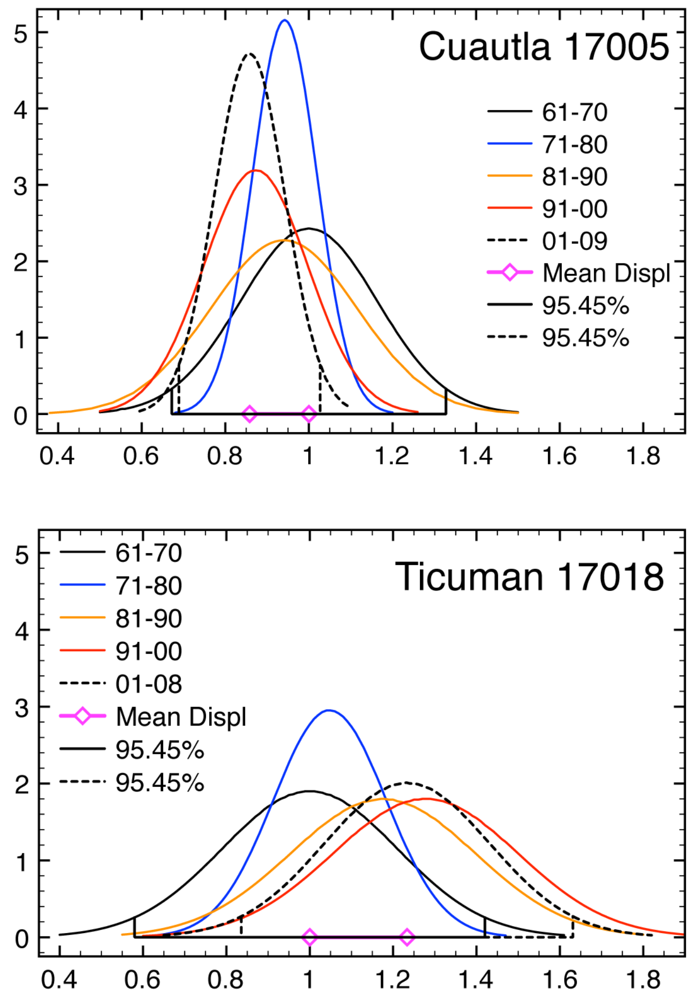

Fig. 6 Probability Density Functions for the precipitation in every decade in two stations: the reiterative displacement of the PDF to the left indicating the decreasing tendency of the precipitation for Cuautla station (upper panel), and the displacement of the PDF to the right indicating the increasing tendency of the precipitation in time for Ticuman station (lower panel).

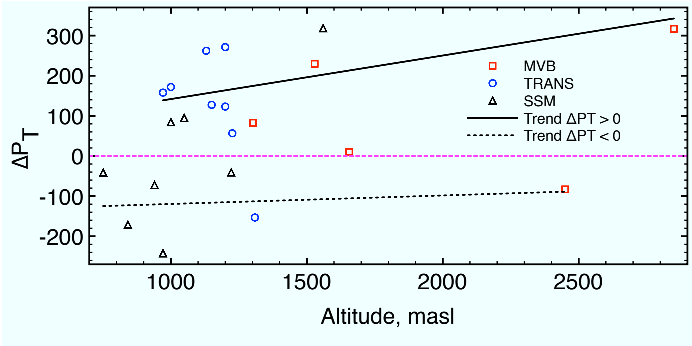

Fig. 7 Variation of total annual precipitation, ΔP_T, for the twenty-one analysed stations over the 42.1 year period of time as a function of their altitude. Note the effect of the altitude in both groups, those with increasing precipitation (upper section) and those with decreasing precipitation (lower section) show the increasing tendency with increasing altitude

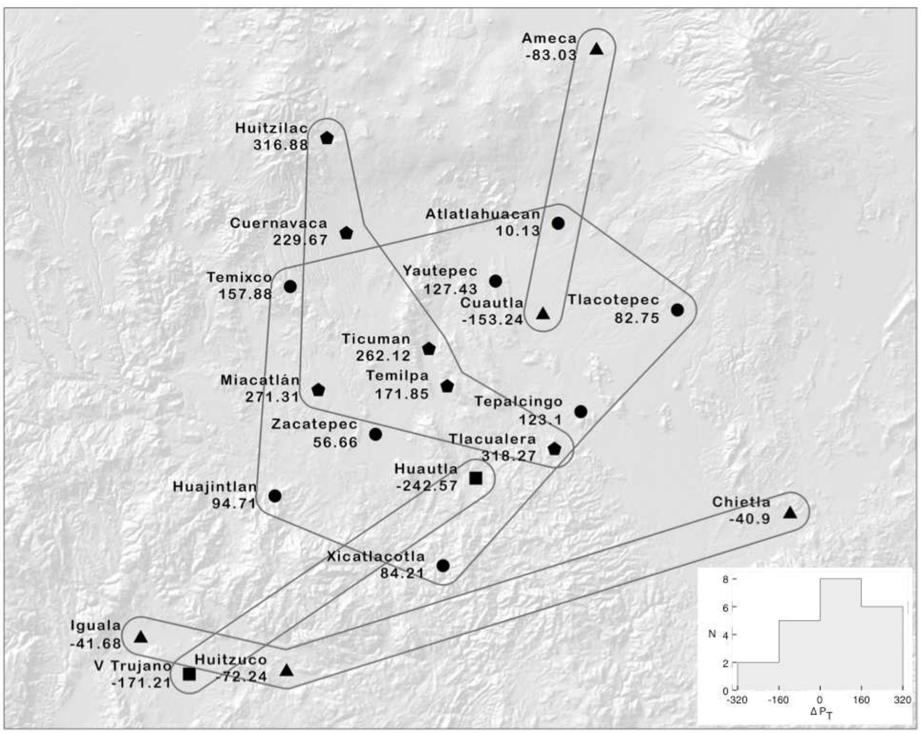

Fig. 8 Clasification of stations according to the change in total precipitation, ΔP_T.

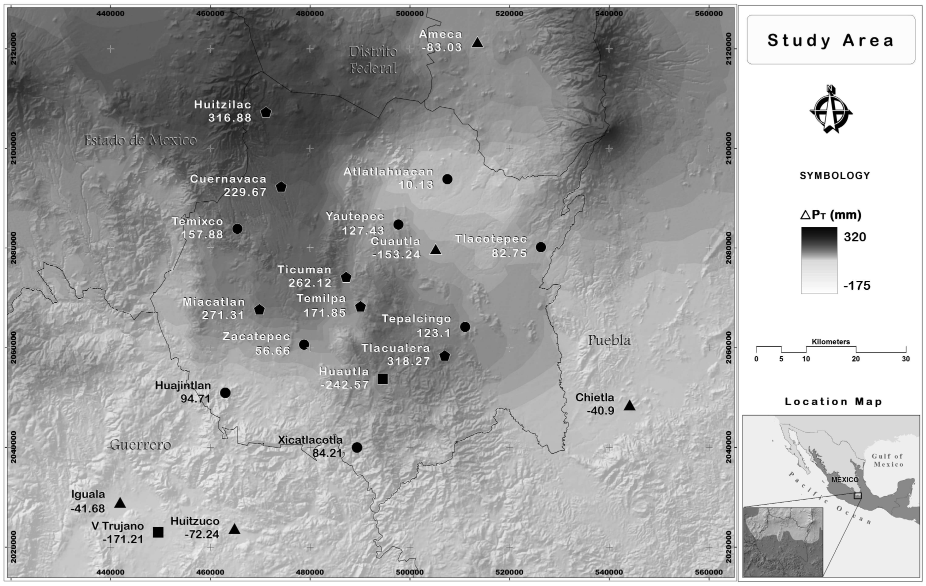

Fig. 9 Interpolation using CoKriging method for the whole analysed region using the information obtained from the stations in Table 2 and excluding the three singular stations mentioned in the text. A gray scale indicates increasing total precipitation towards black and decreasing towards white.