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Precipitation climatology and ENSO influence in the Grijalva sub-basins

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RESUMEN

La cuenca del Grijalva es de gran relevancia en el sur de México debido a que tiene la mayor precipitación y el sistema hidroeléctrico más extenso del país. Además, la cuenca baja ha sido afectada por inundaciones extremas en años recientes. Es la fuente de agua para millones de personas y la industria regional. Para este estudio, la cuenca se dividió en cuatro subcuencas: Angostura, Chicoasén, Malpaso y Peñitas. Cada una de estas subcuencas tiene una presa que ayuda a regular el caudal y a generar energía hidroeléctrica. Para entender mejor la climatología de la región, este estudio utiliza observaciones históricas de lluvia en las subcuencas para describir los patrones de precipitación y su variabilidad. Se procesan varios estadísticos para describir el ciclo anual de la precipitación en cada subcuenca. Los resultados muestran que Angostura, Chicoasén y Malpaso comparten una climatología común, con picos de precipitación en junio y septiembre, y la canícula en julio. Peñitas registra una precipitación considerablemente mayor a lo largo del año, con valores elevados en octubre-noviembre. En todas las subcuencas, los años de La Niña (El Niño) se caracterizan por un incremento (decremento) de la precipitación durante la época lluviosa. El estudio demuestra que la precipitación extrema observada durante los años de La Niña en el verano tardío y el otoño se debe principalmente a un mayor número de ciclones tropicales en el oeste del Caribe y en el Golfo de México. Los resultados del rango intercuartil y otros percentiles de la precipitación mensual proporcionan información adicional que puede ser útil para la operación de las presas.

ABSTRACT

The Grijalva basin is of great relevance in southern Mexico because it receives the highest precipitation and has the most extensive hydroelectric system in the country. In addition, the lower basin has been impacted by extreme flooding in recent years. It is the source of water for several million people and the regional industry. For this study, the basin was divided into four sub-basins: Angostura, Chicoasén, Malpaso, and Peñitas. Each of these sub-basins has a dam that helps regulate the water flow and generate hydroelectric energy. To better understand the region's climatology, this study uses long-term rainfall observations from sub-basins to describe precipitation patterns and their variability. Various statistics are computed to describe the annual precipitation cycle for each sub-basin. The results show that Angostura, Chicoasén, and Malpaso share a common climatology, with precipitation peaks in June and September and a mid-summer drought (MSD) in July. Peñitas receives considerably more precipitation throughout the year, with the highest values in October-November. In all sub-basins, La Niña (El Niño) years are characterized by increased (decreased) precipitation in the rainy season. The study demonstrates that the extreme precipitation observed during La Niña years in late summer and autumn is mainly due to an increased number of tropical cyclones over the western Caribbean Sea and the Gulf of Mexico. The interquartile range and other percentile values of monthly precipitation provide additional information that may be useful for dam management.

Keywords: Grijalva basin, precipitation climatology, annual cycle, extreme rainfall, ENSO, tropical cyclones.

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1. Introduction

The Grijalva basin covers a large region in southern Mexico, encompassing parts of Chiapas, Tabasco, Oaxaca, and Veracruz, as well as Guatemala. Together with the Usumacinta basin, it forms what is known as the Grijalva-Usumacinta system, which accounts for 30 to 40 percent of the total runoff in the country, with a rich biodiversity (Muñoz-Salinas et al., 2023), playing a key role in provisioning, regulating, and supporting ecosystem and cultural services, among which water availability stands out (Mesa-Jurado and Ferro-Azcona, 2016). The Grijalva basin receives significant precipitation annually and generates 40% of the country's hydroelectric energy (Ramírez-Salazar, 2011). Within the Grijalva basin, there are four sub-basins of particular interest: Angostura, Chicoasén, Malpaso, and Peñitas. Each of these sub-basins has a hydroelectric dam of the same name, which helps control the avenues into the lower areas of the basin, regulates water for various uses, and, in particular, generates electricity. Angostura, Chicoasén, and Malpaso receive between 1200 and 1700 mm of precipitation annually, while Peñitas, located in the northwest of Chiapas state, can register up to 4000 mm annually (Rubio-Gutiérrez and Triana-Ramírez, 2006). The high and medium Grijalva sub-basins are surrounded by the Sierra Madre to the south and the Altos and Sierra Norte of Chiapas to the east and north, respectively. The highlands (Sierra Norte of Chiapas) of the low and medium Grijalva intercept the humidity carried by the Gulf of Mexico winds, resulting in year-round precipitation from both tropical (easterly waves and easterly winds, tropical cyclones, and the meridional displacement of the Intertropical Convergence Zone) and winter systems (cold fronts, locally known in the region as *nortes*). Additionally, extreme precipitation events in this region can occur when there is an interaction between tropical cyclones and cold air masses. In 2007 and 2020, extreme events caused by cold fronts interacting with tropical cyclones caused severe flooding in the state of Tabasco, when the Peñitas dam was unable to retain the incoming water due to the extreme precipitation, combined with the runoff from the Usumacinta River.

A deep and detailed knowledge of the amount of precipitation and its variability in the Grijalva sub-basins is of particular importance for the production of hydroelectric energy, the availability of water distributed to the population and industry, the sustainability of the region, and the management of the dams to avoid flooding in the lower region of the Grijalva basin. Therefore, understanding the region's precipitation patterns is a key factor in decision-making. The levels of the dams in the sub-basins must be anticipated well in advance to guarantee energy production and to avoid floods. Angostura and Malpaso dams are the largest of the four, meaning they can be managed using monthly-scale climatological statistics to ensure their operation. On the other hand, the Chicoasén and Peñitas dams are smaller and have limited capacity to retain large volumes of water, as they can fill up in a matter of days if extreme precipitation events occur. The Peñitas sub-basin, in particular, is sensitive to extreme events; thus, accurate meteorological and hydrological forecasts, along with proactive decision-making, are essential to prevent severe flooding.

Few studies have described the precipitation climatology of the Grijalva basin, and none have addressed its sub-basins. Andrade-Velázquez and Medrano-Pérez (2020) used station database to assess the behavior of rainfall in the Grijalva-Usumacinta basin, mapping their spatial patterns over the region and future projections for emissions scenarios (Andrade-Velázquez and Medrano-Pérez, 2021). Other studies examined the influence of El Niño Southern Oscillation (ENSO) conditions in southern Mexico, showing that negative anomalies of precipitation occur over the positive ENSO phase (El Niño), with the opposite happening during the negative phase (La Niña). It has been shown that during El Niño (La Niña) conditions, fewer (more) tropical cyclones occur over the North Atlantic (Gray, 1948; Klotzbach, 2011; Domínguez et al., 2020; Lin et al., 2020), modulating the amount of precipitation over southern Mexico (Domínguez and Magaña, 2018) and therefore in the Grijalva sub-basins.

To understand the precipitation climatology of the Grijalva sub-basins, this study used long-term daily precipitation observations from climatological stations operated by Mexico's National Water Commission (CONAGUA, 2025). The analysis describes the monthly rainfall behavior, examines trends during the 1990-2020 period, and computes percentiles to quantify interannual variability. A comparison of the climatology patterns among sub-basins was performed. Particular attention was given to inter-annual variability at the monthly scale, with various percentiles computed to identify potential precipitation events in a given year. Additionally, an analysis of precipitation variability associated with ENSO was conducted, establishing significant differences between ENSO phases. Historical tropical cyclone data were also used to assess the impact of ENSO phases on the number of cyclones affecting the Grijalva-basin region. It is expected that the results of this study may contribute to improved dam management, considering the differences in precipitation across each sub-basin as well as their natural coupling as a whole system. In addition, the findings may support public policies related to civil protection, energy, and ecosystem conservation.

2. Data and methods

2.1 Precipitation data

The precipitation data were obtained from the Servicio Meteorológico Nacional (SMN), an agency within Mexico's National Water Commission (CONAGUA). The data consists of daily precipitation records for the period 1990-2020, recorded by several stations along the sub-basins (Angostura, Chicoasén, Malpaso, Peñitas) of the Grijalva system based on the basin delineation for the Hydrological Region 30. All sub-basins belonging to the upper and middle Grijalva hydrological subregions are considered, as well as the three sub-basins of the lower Grijalva contributing flow to the Peñitas dam (SEMARNAT, 2010) (Fig. 1). These stations constitute the largest network of climatological stations along the country, with a total of 5400 units (not all stations cover the same time period), providing daily climatological data of maximum and minimum temperature, 24 h accumulated precipitation, and evaporation. Data from these stations are publicly available online on the CONAGUA website (CONAGUA, 2025). For this study, 30 stations were used, some of which are located at the boundaries of the sub-basins. Using the stations of each sub-basin, the arithmetic mean of daily accumulated precipitation was calculated based solely on available daily measurements. All statistics and results obtained in this study were derived from this information. To verify the consistency of the data, the annual accumulated precipitation for each sub-basin was compared with a product from the SMN, yielding very similar results. The number of stations varies over the period of study, with more in

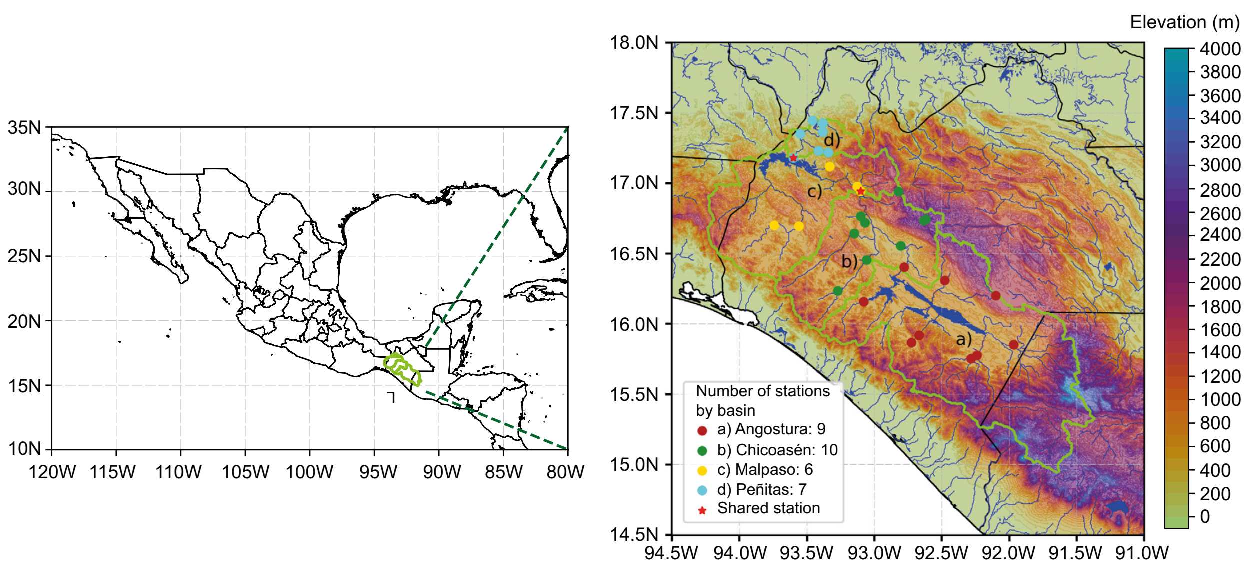

Fig. 1. Elevation map indicating the limits of each sub-basin (light green), the bodies of water and dams (dark blue), and the SMN climatological stations used for this study (with solid dots and letters for the dams): (a) Angostura (stations in red), (b) Chicoasén (stations in green), (c) Malpaso (stations in yellow), and (d) Peñitas (stations in cyan). Shared stations located at the boundaries of the sub-basins are represented by stars.

Angostura and Chicoasén and fewer in Malpaso and Peñitas, although in the last 20 years, the number of stations increased (Fig. 2).

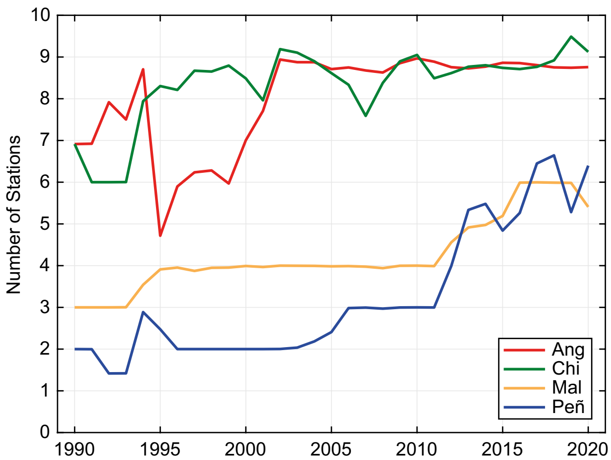

Fig. 2. Yearly average number of stations for each sub-basin.

2.2 ENSO classification and statistical differences

To assess the influence of the ENSO phenomenon on precipitation in the sub-basins of the Grijalva system during its neutral, El Niño, and La Niña phases, a monthly classification was conducted from 1990 to 2020 (Table I). The classification was based on the Oceanic Niño Index (ONI) of the Climate Prediction Center (NOAA, 2024). To discern statistical differences between phase means, a set of non-parametric statistical tests was applied in all cases, including the Kruskal-Wallis test. To identify which group pairs differed significantly, a Dunn's post hoc test was conducted. All tests were conducted with a two-sided 95% confidence interval, so a resulting p-value less than 0.05 indicated a significant difference between the means. Subsequently, a comparison was made with the results that would have been obtained using parametric tests, and no statistical differences were identified (data not shown).

2.3 Tropical cyclones

An analysis of variability in the trajectories of tropical cyclones (TCs) during ENSO phases in the Grijalva was conducted. For this purpose, a potential region of influence over the Grijalva sub-basins was established. A rectangle was delimited whose limits have an extension of 7.5º (~ 800 km) from the most remote location of each cardinal point of the Grijalva basin. This broader area allows for the inclusion of a greater number of TCs in the statistical analysis and is not intended to estimate the amount of precipitation associated with TCs in the study basin. The trajectories of hurricanes for the North Atlantic and Northeast Pacific oceans were obtained from the HURDAT2 database of the National Hurricane Center (Landsea and Franklin, 2013).

As the trajectories were classified by month for each ENSO phase (Table I), it is possible to group and count the number of years associated with each phase, such that the total number of years for any given calendar month is always 31 (since the period 1990-2020 spans 31 years). For each of these groups, the number of TCs that occurred in each ocean was recorded. To compare TC occurrence as a function of ENSO phase, it is useful to normalize the count. Since the number of years under each ENSO phase is not the same, the total number of TCs in each group was divided by the number of years corresponding to each phase (i.e., it was considered a normalized value). When a TC occurred across two months, it was divided into fractions, assigning to each month the corresponding fraction of its trajectory, such that the sum of the fractions equaled 1.

3. Results and discussion

3.1 Precipitation climatology

The precipitation climatology in the Grijalva sub-basins is characterized by a dry season from November to April and a rainy season from May to October. During the rainy season, a relative minimum known as mid-summer drought (MSD) occurs (Perdigón-Morales et al., 2017; Corrales-Suastegui et al., 2019). Results show that long-term monthly means of precipitation for each sub-basin are consistent with previously reported precipitation climatologies for the Grijalva basin, with a mid-summer minimum in July and two relative maximums in June and September (Fig. 3, Table II), although those studies were not conducted at the sub-basin scale nor with monthly resolution (Arreguín-Cortés et al., 2014; Andrade-Velázquez and Medrano-Pérez, 2021). Figure 4 shows the annual means and their trend, while Table II presents the average precipitation

Table I. Monthly classification by ENSO phase for 1990-2020.

Year	Month											
	1	2	3	4	5	6	8	8	9	10	11	12
1990	0	0	0	0	0	0	0	0	0	0	0	0
1991	0	0	0	0	1	1	1	1	1	1	1	1
1992	1	1	1	1	1	1	0	0	0	0	0	0
1993	0	0	0	0	0	0	0	0	0	0	0	0
1994	0	0	0	0	0	0	0	0	1	1	1	1
1995	1	1	1	0	0	0	0	2	2	2	2	2
1996	2	2	2	0	0	0	0	0	0	0	0	0
1997	0	0	0	0	1	1	1	1	1	1	1	1
1998	1	1	1	1	1	0	2	2	2	2	2	2
1999	2	2	2	2	2	2	2	2	2	2	2	2
2000	2	2	2	2	2	2	2	2	2	2	2	2
2001	2	2	0	0	0	0	0	0	0	0	0	0
2002	0	0	0	0	0	1	1	1	1	1	1	1
2003	1	1	0	0	0	0	0	0	0	0	0	0
2004	0	0	0	0	0	0	1	1	1	1	1	1
2005	1	1	0	0	0	0	0	0	0	0	2	2
2006	2	2	2	0	0	0	0	0	1	1	1	1
2007	1	0	0	0	0	2	2	2	2	2	2	2
2008	2	2	2	2	2	2	0	0	0	0	2	2
2009	2	2	2	0	0	0	1	1	1	1	1	1
2010	1	1	1	0	0	2	2	2	2	2	2	2
2011	2	2	2	2	2	0	2	2	2	2	2	2
2012	2	2	2	2	0	0	0	0	0	0	0	0
2013	0	0	0	0	0	0	0	0	0	0	0	0
2014	0	0	0	0	0	0	0	0	0	1	1	1
2015	1	1	1	1	1	1	1	1	1	1	1	1
2016	1	1	1	1	0	0	0	2	2	2	2	2
2017	0	0	0	0	0	0	0	0	0	2	2	2
2018	2	2	2	2	0	0	0	0	1	1	1	1
2019	1	1	1	1	1	1	0	0	0	0	0	0
2020	0	0	0	0	0	0	0	2	2	2	2	2

Neutral = 0, El Niño = 1, La Niña = 2.

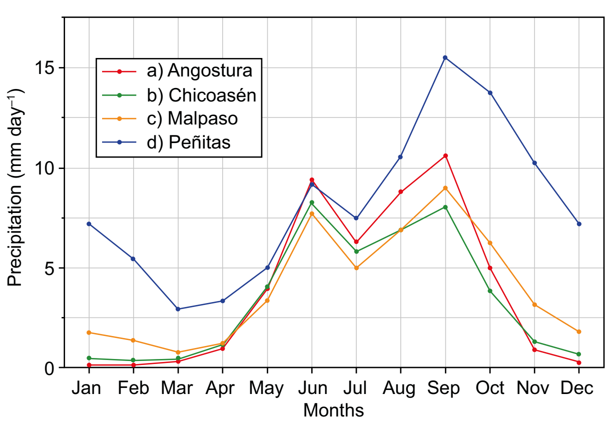

Fig. 3. Long-term monthly mean precipitation of the sub-basins in the Grijalva basin: (a) Angostura (red line), (b) Chicoasén (green line), (c) Malpaso (orange line), and (d) Peñitas (blue line).

Table II. Long-term monthly mean of the daily precipitation and monthly accumulated precipitation of the sub-basins in the Grijalva basin for the period 1990-2020. Annual mean and accumulated precipitation are also shown, as well as the volume (precipitation multiplied by the area of each sub-basin).

Month		1	2	3	4	5	6	7	8	9	10	11	12	Annual mean (mm day^{-1})	Per sub-basin (m^3 day^{-1})
Sub-basin	Area (km^2)	Monthly mean of the daily precipitation (mm day^{-1})													
(a)	19600	0.14	0.12	0.3	0.95	3.96	9.4	6.27	8.79	10.6	5.01	0.9	0.28	3.89	7.62E+07
(b)	7450	0.48	0.35	0.44	1.1	4.02	8.24	5.8	6.88	8.02	3.83	1.28	0.66	3.42	2.55E+07
(c)	9950	1.74	1.37	0.77	1.2	3.35	7.72	4.96	6.86	8.95	6.23	3.18	1.8	4.01	3.99E+07
(d)	1260	7.18	5.44	2.93	3.34	4.99	9.15	7.47	10.5	15.5	13.7	10.3	7.18	8.14	1.03E+07
		Monthly accumulated precipitation (mm)												Annual accumulated (mm)	Per sub-basin (m^3)
(a)		4.4	3.6	9.1	28.6	123	282	194	273	318	155	27	8.7	1426	2.79E+10
(b)		14.8	10.5	13	33.1	125	247	180	213	241	119	38.4	20.5	1254.4	9.34E+09
(c)		53.9	40.6	22	36.1	104	232	154	213	269	193	95.5	55.9	1467.6	1.46E+10
(d)		223	161	83.6	100	155	275	232	326	465	426	308	222	2975.2	3.76E+09

(a) Angostura, (b) Chicoasén, (c) Malpaso, and (d) Peñitas.

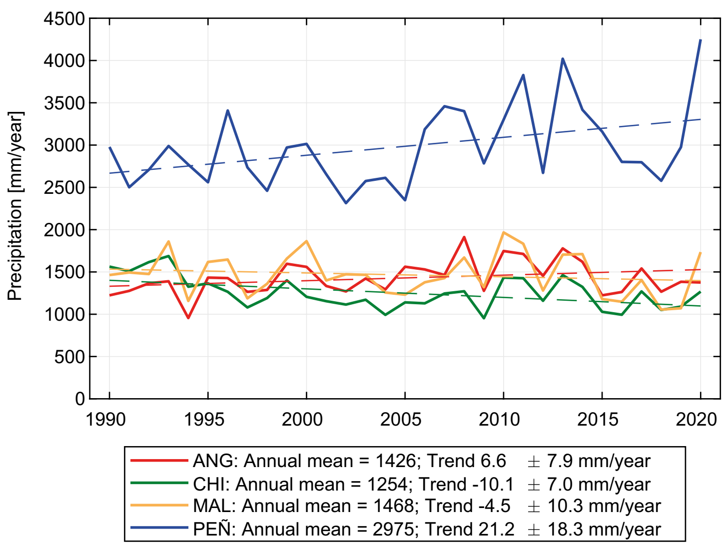

Fig. 4. Annual precipitation and trends for the period 1990-2020.

values for each month and for the entire year of the four sub-basins. In Angostura, Chicoasén, and Malpaso, the precipitation patterns and amounts are similar, with a dry season followed by a rainy season that includes a clearly defined MSD. These three sub-basins exhibit a first peak in June, a second one in September, and an MSD mainly in July, according to Perdigón-Morales et al. (2017) and Straffon et al. (2020). The mean yearly precipitation is very similar between these sub-basins. The Peñitas sub-basin, as the other three, has peaks in June and September, but it receives considerably more precipitation from September to February compared to the other sub-basins. The location of the Peñitas sub-basin is a key factor in its intense precipitation regimen during autumn and winter, with precipitation caused by cold fronts that interact with other systems that transport moisture from the Gulf of Mexico, which, favored by topographic convection, develops precipitation (López-Méndez, 2009; Andrade-Velázquez and Medrano-Pérez, 2020). Additionally, the Peñitas sub-basin is the only one that shows a statistically significant positive trend in precipitation during the study period, although the time series exhibits considerable interannual variability. In contrast, the trend for Chicoasén is negative. In the case of Angostura and Malpaso, although they exhibit positive and negative trends, respectively, these are not statistically significant when considering the uncertainty range (Fig. 4). Based on the previous results, it is not possible to conclude that there is a single precipitation trend within the Grijalva basin; therefore, further studies with a climate change perspective are needed to identify the implications for the amount of hydroelectric energy that may be generated in the future, as well as the considerations that dam operators should take into account for planning and management.

In the Peñitas sub-basin, annual accumulated rainfall is at least twice as high as in the other sub-basins. However, the total volume in Peñitas is smaller due to its size (see Table II). To quantify the relative magnitude of the MSD for each sub-basin, the proportions between monthly means that have relative maxima or minima were calculated as shown in Table III. For Angostura and Malpaso, the June-July and August-July ratios are similar. For Peñitas, the September-July ratio is considerably higher, whereas for Chicoasén the average rainfall in September is only slightly greater than in July. For the September-June relationship, that is, between the two precipitation peaks, the ratio is close to 1, except for Peñitas, where it is considerably higher. These results show that the Peñitas sub-basin has a different climatology than the other in terms of the amount of precipitation and its distribution throughout the annual cycle.

Table III. Ratios of mean precipitation in the Grijalba sub-basins for June-July, August-July, September-July, and September-June, for the period 1990-2020.

Sub-basin	jun/jul	ago/jul	sep/jul	sep/jun
(a)	1.5	1.4	1.69	1.13
(b)	1.42	1.19	1.38	0.97
(c)	1.56	1.38	1.8	1.16
(d)	1.22	1.41	2.07	1.69

(a) Angostura, (b) Chicoasén, (c) Malpaso, and (d) Peñitas.

The 25th, 50th, 75th, 95th, and 99th percentiles were computed and plotted, as well as the maximum and minimum average daily precipitation of each month of the Grijalva sub-basins (Fig. 5). The 25th, 50th and 75th percentiles show a similar behavior as the monthly mean, with peaks in June and September, and relative minimums between these peaks. This means that in at least 75% of the years, precipitation over the sub-basins exhibits a strong MSD, according to climatology. The behavior of the 95th, 99th percentiles, and the maximum, differs from the other statistics and varies for each sub-basin. Several patterns are observed. In Angostura, the 99th percentile and the maximum have a year-around peak in August, with most of the maximum precipitation occurring between July and October. Chicoasén shows a bimodal behavior, having peaks in June and August for the 95th, 99th percentiles, and the maximum, and a clear MSD in July. In Malpaso, the maximum and 99th percentile also peak in June and August, with highest values of the maximum precipitation occurring from June to October, and a clear midsummer minimum in July. The Peñitas sub-basin exhibits a completely different climatology compared to the other sub-basins. For the percentiles, absolute maximum, and minimum, the first peak occurs in June, and a second peak occurs in September. However, for the 95th, 99th percentiles, and the absolute maximum, the peaks occur in October-November. This suggests that under extreme conditions, such as the interaction of a cold front with a tropical system, extreme precipitation can occur, as it did in November of 2020 when Cold Front 11 interacted with Hurricane Eta (CONAGUA, 2020), causing a severe flooding in Tabasco.

The importance of considering the interquartile range and percentiles, such as the 95th and 99th, lies in enabling dam system operators to respond appropriately to extreme events. For example, November in the Peñitas sub-basin exhibits the largest range of variability among all sub-basins (Fig. 5d). It has an average precipitation of just over 10 mm day^{-1}, which nearly doubles (triples) at the 95th (99th) percentile. This highlights the relevance of incorporating

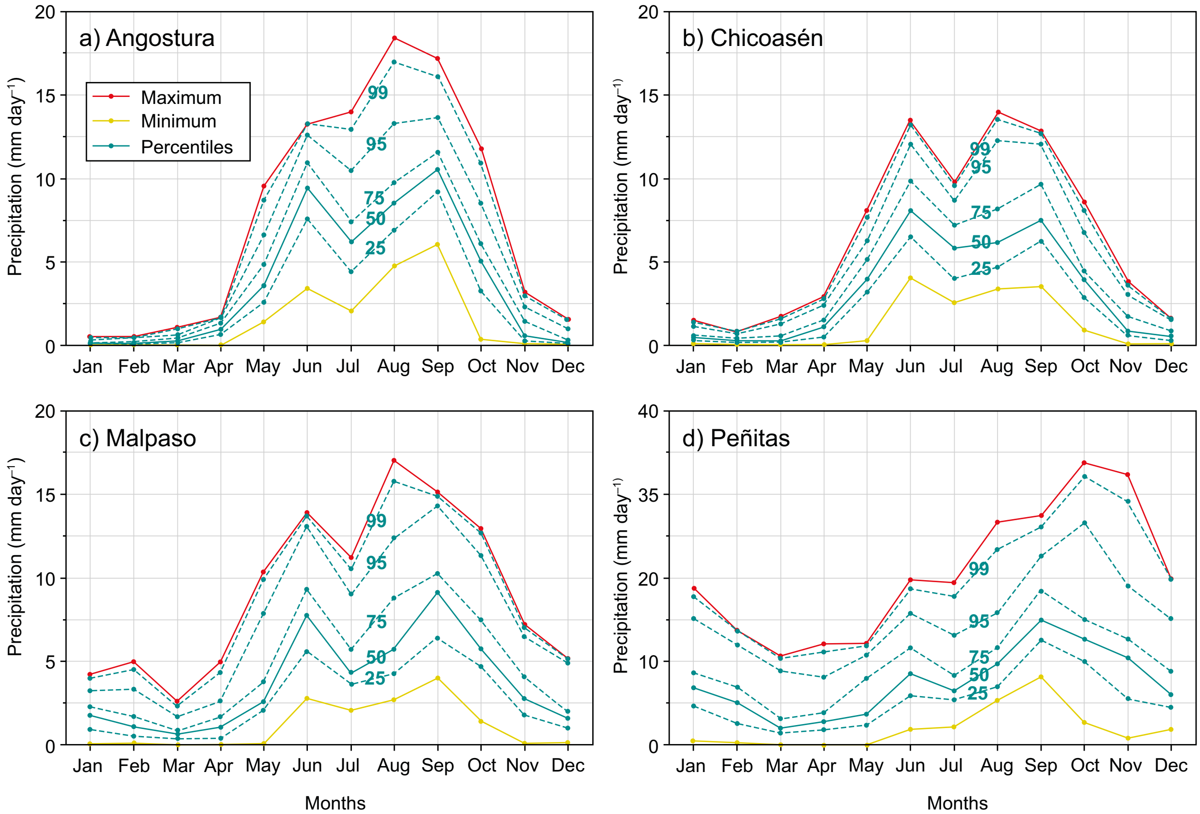

Fig. 5. 25th, 50th, 75th, 95th, and 99th percentiles of the monthly mean of the daily precipitation (green lines), maximum (red line), and minimum (yellow-gold line) values for the period from 1990 to 2020 in the Grijalva sub-basins. (a) Angostura, (b) Chicoasén, (c) Malpaso, and (d) Peñitas.

broader ranges of variability in the planification of dam operation.

3.2 ENSO influence

Precipitation over the sub-basins of the Grijalva behaves differently according to the ENSO phase. Figure 6 shows a comparison of the monthly mean for each ENSO phase and sub-basin. The neutral episodes follow the seasonal mean in both behavior and precipitation amount across all sub-basins. The patterns for El Niño and La Niña differ across sub-basins. El Niño's mean in Angostura follows the main mean, but from June to September precipitation decreases to a level similar to the 25th percentile. The opposite occurs for La Niña's mean, which has similar precipitation to that of the 75th percentile. In Chicoasén, El Niño's mean follows the precipitation of the 25th percentile line from July to September, while La Niña's mean exceeds the 75th percentile in August. For Malpaso, El Niño's mean behavior is similar to that in Chicoasén sub-basin, but for La Niña's mean, the precipitation exceeds the 75th percentile during several months. In Peñitas, the differences between phases are clearer because of the amount of precipitation in the sub-basin: El Niño's mean precipitation is similar to that of the 25th percentile in April-May and July-October, while La Niña's mean exceeds the 75th percentile in July, August, and October. It's worth noting that in December, the mean neutral episodes for Malpaso and Peñitas are similar to or exceed the 75th percentile.

To assess significant differences between the phase means across months and sub-basins, nonparametric tests were performed. In Table IV, the p-values of the tests are shown. A statistical difference was considered only when the p-value was lower than 0.05. The results in Table IV show the same trend as in Fig. 4. For the rainy months July, August, and

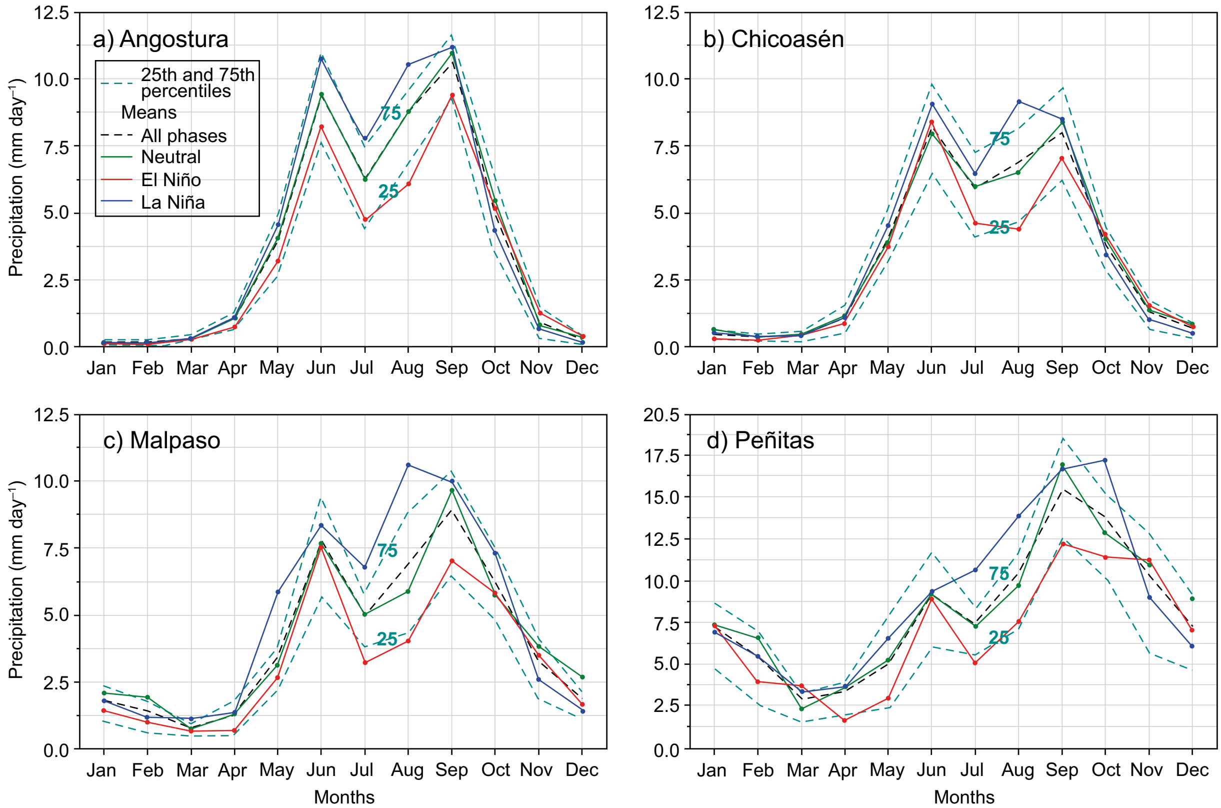

Fig. 6. Monthly mean daily precipitation for each phase: neutral (green line), El Niño (red line), and La Niña (blue line) for the period 1990-2020 in the Grijalva sub-basins. (a) Angostura, (b) Chicoasén, (c) Malpaso, and (d) Peñitas. Additionally, the mean that includes all phases (black dashed line) and the 25th and 75th percentiles (green dashed line) are shown.

Table IV. Monthly mean of accumulated precipitation, their corresponding standard deviations, and the p-values from non-parametric tests for the period 1990- 2020, for each sub-basin of the Grijalva and ENSO phase. The pair comparisons were performed as follows: Nt vs. No, Nt vs. Na, and No vs. Na.

Basin	Month	Mean (mm)			Std (mm)			p-value	Post-hoc p-value		
		Nt	No	Na	Nt	No	Na		Nt_No	Nt_Na	No_Na
a)	1	4.55	4.18	4.34	2.94	3.96	4.39	0.865	1.0	1.0	1.0
	2	3.93	1.35	4.85	04.08	1.24	4.15	0.119	0.345	1.0	0.144
	3	8.91	9.57	9.26	5.36	6.53	9.26	0.927	1.0	1.0	1.0
	4	29.09	21.67	32.65	12.6	16.9	12.87	0.567	1.0	1.0	0.86
	5	125.96	99.48	141.33	46.84	33.47	96.13	0.578	0.894	1.0	1.0
	6	282.66	246.75	322.4	68.53	46.75	64.54	0.128	0.523	0.718	0.131
	7	194.4	148.13	240.68	83.49	32.16	63.93	0.077	0.656	0.364	0.073
	8	273.42	188.53	326.74	65.54	21.48	98.16	**0.001**	**0.013**	0.544	**0.001**
	9	329.31	282.4	335.9	66.42	57.76	46.89	0.172	0.404	1.0	0.234
	10	169.18	160.75	134.53	81.5	39.27	76.44	0.548	1.0	1.0	0.871
	11	23.94	38.12	20.15	22.42	18.72	26.27	**0.029**	0.226	1.0	**0.027**
	12	11.32	11.73	4.23	14.09	12.34	3.75	0.213	1.0	0.543	0.32

(a) Angostura, (b) Chicoasén, (c) Malpaso, and (d) Peñitas.
ENSO phases: No = El Niño, Nt = neutral, Na = La Niña.

Table IV. Monthly mean of accumulated precipitation, their corresponding standard deviations, and the p-values from non-parametric tests for the period 1990- 2020, for each sub-basin of the Grijalva and ENSO phase. The pair comparisons were performed as follows: Nt vs. No, Nt vs. Na, and No vs. Na.

Basin	Month	Mean (mm)			Std (mm)			p-value	Post-hoc p-value		
		Nt	No	Na	Nt	No	Na		Nt_No	Nt_Na	No_Na
b)	1	18.66	9.63	15.61	13.13	4.79	8.22	0.187	0.267	1.0	0.44
	2	11.05	7.14	10.91	06.05	3.0	5.75	0.225	0.289	1.0	0.58
	3	14.38	13.18	12.89	11.23	17.14	9.92	0.55	0.828	1.0	1.0
	4	35.1	25.79	32.38	23.46	27.9	11.89	0.557	0.919	1.0	1.0
	5	124.03	116.05	140.72	43.67	51.13	72.22	0.996	1.0	1.0	1.0
	6	239.52	251.75	272.3	64.7	89.96	32.28	0.457	1.0	0.642	1.0
	7	185.4	142.52	199.8	63.97	27.26	43.18	0.19	0.471	1.0	0.226
	8	202.41	136.58	283.85	57.33	23.14	92.63	**0.002**	0.063	0.18	**0.001**
	9	250.96	211.42	254.55	76.99	49.24	67.75	0.312	0.524	1.0	0.558
	10	121.11	129.04	105.57	49.89	34.3	61.89	0.314	1.0	0.562	0.552
	11	42.0	45.56	29.6	23.78	22.38	33.82	**0.033**	1.0	0.199	**0.04**
	12	25.49	22.58	15.05	13.91	15.18	9.27	0.296	1.0	0.382	0.987
c)	1	63.64	42.76	54.38	32.99	30.63	22.31	0.353	0.482	1.0	0.94
	2	52.94	26.92	32.11	39.38	15.41	18.95	0.279	0.443	0.638	1.0
	3	20.86	18.97	33.12	9.99	12.17	20.63	0.139	1.0	0.255	0.242
	4	39.17	19.32	39.87	32.53	22.63	23.73	0.239	0.355	1.0	0.386
	5	95.75	81.41	181.03	51.63	39.87	95.61	0.183	1.0	0.197	0.505
	6	228.97	225.15	249.78	77.93	97.69	98.86	0.833	1.0	1.0	1.0
	7	154.12	98.32	208.21	55.11	22.35	79.94	**0.01**	0.046	0.675	**0.009**
	8	181.06	124.0	327.47	70.18	34.37	92.9	**0.0**	0.366	**0.01**	**0.001**
	9	288.15	209.78	298.83	91.76	50.88	85.7	0.046	0.164	1.0	0.055
	10	176.97	178.74	225.46	86.78	49.7	102.54	0.365	1.0	0.468	1.0
	11	113.18	103.6	75.55	61.92	46.88	51.55	0.175	1.0	0.246	0.508
	12	81.23	49.88	41.81	44.2	39.19	23.42	**0.032**	0.161	**0.032**	1.0
d)	1	228.03	225.14	214.01	89.2	168.85	117.68	0.716	1.0	1.0	1.0
	2	185.06	111.17	154.56	108.81	52.31	92.84	0.278	0.328	1.0	1.0
	3	72.25	114.56	103.67	34.26	109.1	91.59	0.879	1.0	1.0	1.0
	4	109.85	48.2	110.93	86.09	31.25	52.73	0.175	0.325	1.0	0.228
	5	163.25	92.25	203.0	101.54	78.1	102.7	0.133	0.244	1.0	0.214
	6	276.11	265.27	279.91	136.51	76.25	122.34	0.972	1.0	1.0	1.0
	7	224.38	156.98	329.0	76.53	58.26	142.52	**0.022**	0.216	0.324	**0.017**
	8	301.08	236.84	430.19	86.03	107.65	156.01	**0.007**	0.339	0.117	**0.006**
	9	508.11	366.83	500.38	134.45	94.85	107.54	**0.037**	0.057	1.0	0.094
	10	397.27	351.1	532.1	175.16	121.73	265.86	0.335	1.0	0.565	0.629
	11	327.8	335.78	269.1	179.89	102.7	228.23	0.112	1.0	0.357	0.157
	12	275.09	217.04	187.42	141.81	147.67	78.17	0.378	0.735	0.6	1.0

(a) Angostura, (b) Chicoasén, (c) Malpaso, and (d) Peñitas.
ENSO phases: No = El Niño, Nt = neutral, Na = La Niña.

September, the tests show a difference between phases, particularly in August. In all sub-basins, the mean values for El Niño years are substantially lower than those for the other phases. In particular, during La Niña years, the tests also show a statistical difference across all sub-basins, with higher precipitation values than in El Niño years in August, and in some cases also in July and November (see right-hand columns of Table IV). Compared to years with a neutral ENSO phase, La Niña episodes show higher precipitation values—even if statistical significance is not achieved—in August across all sub-basins, in July in Angostura, Malpaso, and Peñitas, and in October in Peñitas. During the dry season, the mean values are very low due to the lack of precipitation, although the tests do not show significant differences across all sub-basins. For Angostura and Malpaso, a significant difference is observed in November between the El Niño and La Niña phases; for Peñitas, there is no difference apart from summer. These results provide clear evidence that during months with higher precipitation in the rainy season, precipitation is consistently lower in El Niño years and significantly higher in La Niña years. The dry season shows a more complex pattern across sub-basins, with relatively important higher values during extreme years in the Peñitas sub-basin.

3.3 Tropical cyclones

A count of the trajectories of TCs that occurred between 1990 and 2020 in a region with potential precipitation influence over the Grijalva sub-basins was performed. Table V shows the total and normalized number of TC by month, ENSO phase, and ocean. The comparisons between phases are clearer with the normalized count, because it divides the total number of TCs by the number of years that occurred in each phase, as described in section 2.3. The normalized count was graphed in Figure 7. In the Atlantic, during the summer and autumn of El Niño years, the number of TCs is very low compared to the other phases, while La Niña years have a higher number of TCs (Fig. 5a). During August, September, and October, La Niña years have at least 7.5, 3.6, and 2.5 more TCs than El Niño, respectively. For the Pacific, during May and August in El Niño years, there are considerably fewer TCs than in the other ENSO phases (Fig. 5b). In September and October of La Niña years, there are 2.8 and 2.1 fewer TCs than during El Niño years. Figure 8 displays the trajectory of TCs that occurred in the region over the period of interest, showing the spatial pattern of all the trajectories. For the Atlantic (Gulf of Mexico and Caribbean Sea), there is a clear pattern of very few TCs during El Niño years (Fig. 6b). The opposite occurs for the neutral and La Niña phases (Fig. 6a, c). In the Pacific, the number of trajectories looks similar for El Niño and La Niña years, which is explained by the fact that in some months each ENSO phase has more or fewer TC than the other. In neutral years, there is a clear abundance of TCs in the Pacific Ocean (Fig. 6a). These results are consistent with the differences shown in Table IV and agree with the reduction in precipitation during El Niño years, with a decrease in the number of TCs from the Atlantic. On the other hand, it is inferred that the lower number of TCs in

Table V. Number of tropical cyclones (TCs) for the Atlantic and Pacific under each ENSO phase and for each month in the potential influence zone of the Grijalva sub-basins from 1990 to 2020. Total number of events and normalized counts by the number of months under each phase.

Month	Number of ENSO episodes			Total number of TCs in the Atlantic			Normalized number of TCs in the Atlantic			Total number of TCs in the Pacific			Normalized number of TCs in the Pacific		
	Nt	No	Na	Nt	No	Na	Nt	No	Na	Nt	No	Na	Nt	No	Na
1	11	10	10	0	0	0	0	0	0	0	0	0	0	0	0
2	12	9	10	0	0	0	0	0	0	0	0	0	0	0	0
3	15	7	9	0	0	0	0	0	0	0	0	0	0	0	0
4	20	5	6	0	0	0	0	0	0	0	0	0	0	0	0
5	21	6	4	3.44	0	0.5	0.16	0	0.12	11.8	0	2	0.56	0	0.5
6	20	6	5	12.2	1	2.86	0.61	0.17	0.57	23.8	7	5.5	1.19	1.17	1.1
7	19	6	6	6.75	1	3.27	0.36	0.17	0.55	19	3.75	4	1	0.62	0.67
8	16	6	9	15	1	11.5	0.94	0.17	1.28	11	2.25	9.87	0.69	0.38	1.1
9	13	9	9	9.31	4	14.2	0.72	0.44	1.58	12	8.9	3.13	0.93	0.99	0.35
10	11	10	10	12.9	5	12.5	1.17	0.5	1.25	11.6	10.3	5	1.06	1.03	0.5
11	9	10	12	1.82	1	5.79	0.2	0.1	0.48	1	2.1	3	0.11	0.21	0.25
12	9	10	12	0	0	1	0	0	0.08	0	0	0	0	0	0

ENSO phases: No = El Niño, Nt = neutral, Na = La Niña.

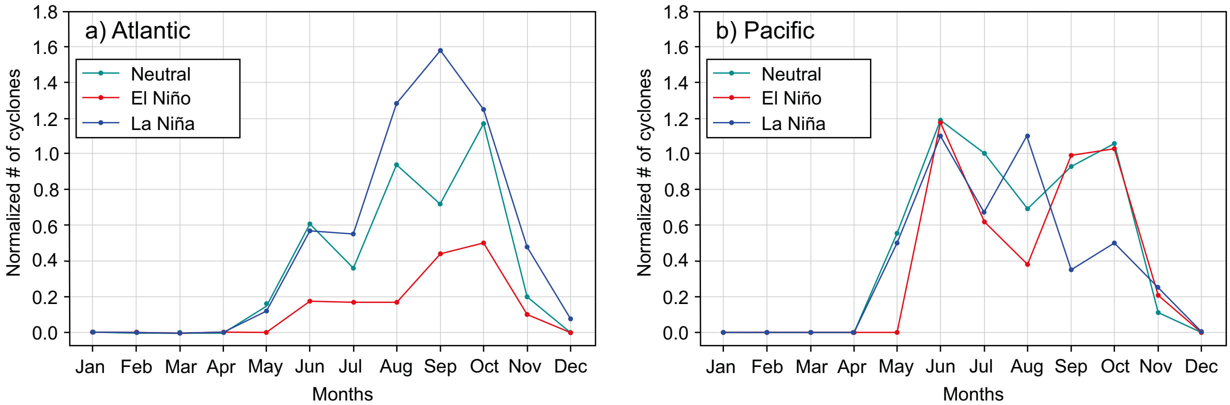

Fig. 7. Normalized number of tropical cyclones by month in (a) Atlantic and (b) Pacific, grouped by ENSO phase: neutral (green line), El Niño (red line), and La Niña (blue line), in the potential influence zone of the Grijalva sub-basins from 1990 to 2020.

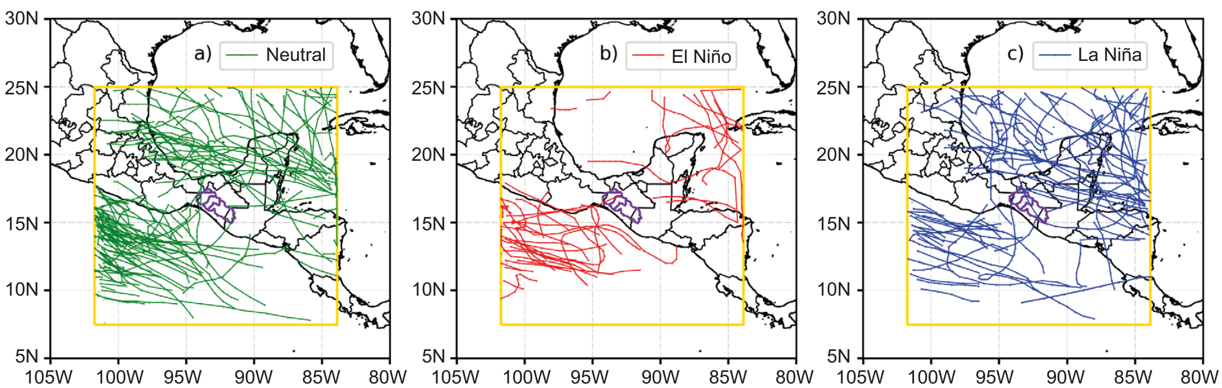

Fig. 8. Tropical cyclones from 1990 to 2020 from the Atlantic and Pacific within the potential influence zone (yellow-gold) over the Grijalva sub-basins (purple) by ENSO phase: (a) neutral (green), (b) El Niño (red), and (c) La Niña (blue).

the Pacific during La Niña years does not have a great impact on the precipitation over the Grijalva sub-basins. Table IV shows that in comparison to the other phases, La Niña's mean precipitation is lower in November for all sub-basins. However, in Peñitas, the second month with maximum precipitation can occur until November (Fig. 5d). This is explained by the higher number of TCs in the Atlantic during November, which is three and two times higher than in the neutral and El Niño phases, respectively.

4. Conclusions

The precipitation climatology of the Grijalva sub-basins of Angostura, Chicoasén, Malpaso, and Peñitas was thoroughly analyzed. It was found that the Angostura, Chicoasén, and Malpaso sub-basins share a similar precipitation regime, with peaks in June and September and a clear MSD in July. The Peñitas sub-basin receives considerably more precipitation from September to February due to its geographical and climatological conditions and it is also the only one that shows a positive trend in precipitation during the study period. In contrast, the trend for Chicoasén is negative. For Angostura and Malpaso, the trends are positive and negative, but neither is statistically significant. The results obtained do not support the conclusion that there is a single precipitation trend within the Grijalva basin. Therefore, further studies with a climate change perspective are needed to assess potential implications for future hydroelectric energy generation.

When percentiles and maximum values were computed, the distribution of precipitation throughout the year changed. Maximum precipitation in the Angostura, Chicoasén, and Malpaso sub-basins occurs in August, whereas in Peñitas it occurs in October-November. In all sub-basins, the 99th percentile (and sometimes the 95th percentile) follows the absolute maximum, while the 25th, 50th, and 75th percentiles, and the minimum follow the average seasonal pattern. Interquartile range and other percentile values, in addition to the commonly used mean and return time of synoptic events, provide information to improve monthly and seasonal scenarios that may be useful for dam operations to mitigate flooding.

A comparison of monthly mean precipitation among ENSO phases (neutral, El Niño, and La Niña) for each sub-basin was conducted using non-parametric tests. It was found that during La Niña episodes, precipitation over the Grijalva sub-basins is significantly higher from July to September, particularly in August. In all cases, the mean precipitation of the La Niña phase is similar to the 75th percentile. During the El Niño phase, the opposite occurs in the same months of the rainy period, with considerably lower precipitation, similar to the 25th percentile. In the dry season, precipitation patterns among ENSO phases are more complex and vary across the sub-basins. An analysis of historical TC trajectories over the Grijalva potential influence zone was performed. It showed that during La Niña years, there is a considerably higher number of TCs in the northwestern Caribbean Sea, while during El Niño years, there are considerably fewer TCs. For the Pacific Ocean, the number of TCs varies among ENSO phases throughout the year. It can be concluded that during La Niña years, the presence of more TCs in the Atlantic causes a higher amount of precipitation over the Grijalva sub-basins.

The assessment of historical precipitation in the Grijalva sub-basins, considering multiple statistics and ENSO variability, should aid decision-making on dam management in these sub-basins. To prevent floods in the Lower Grijalva region, particular attention must be paid to extreme (maximum) precipitation, especially in the Peñitas sub-basin, which experiences intense precipitation in autumn (October-November). This is particularly critical during La Niña years when there is a greater abundance of TCs in the Atlantic.

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